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SOFT X-RAY PHOTOEMISSION

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This technical report has been reviewed and approved for publication.

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Project Engineer

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This work was undertaken to develop a capability to predict photoemission from materials for soft x-ray sources. By soft, ~~we mean~~ x-rays ~~with~~ have energies of a few keV or less. The Boltzmann equation was solved for the electron flux - from this flux, other quantities of interest may be obtained, e.g., the photoemission yields. Three materials have been examined: aluminum, aluminum oxide, and silicon dioxide. Back photoemission yields are presented in this report for these materials. For aluminum, an extensive series of runs was made. In particular, results were obtained for a series of narrow Gaussian

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ITEM 20: ABSTRACT (Continued)

photon distributions from 0.5 to 10 keV and for blackbody spectra over a temperature range from 1 to 10 keV.

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Section 1

INTRODUCTION AND SUMMARY

This work was undertaken to develop a capability to predict photoemission from materials for soft x-ray sources. By soft, we mean x-rays with energies of a few keV or less. The electron transport description required for soft x-ray sources is significantly different than the standard multiple scattering - continuous slowing down approach used at higher photon energies.[1-5] At low energies, the standard approach must be abandoned in favor of the more exact single scattering approach which requires detailed scattering energy loss information for each important electron interaction. Said another way, the two parameter description, the parameters being the stopping power and

---

[1] W. L. Chadsey, "POEM," AFCRL Report TR-75-0327 (1975).

[2] H. M. Colbert, "SANDYL," Sandia Laboratories, SLL-74-0012 (1974).

[3] M. J. Berger and S. M. Seltzer, "Electron and Photon Transport Programs," (I) NBS Report 9836, (II) NBS Report 9837.

[4] T. A. Dellin and C. J. MacCallum, IEEE Trans. Nuc. Sci., NS-20, No. 6, 91 (1973).

[5] J. C. Garth and J. V. O'Brien, IEEE Trans. Nuc. Sci., NS-20, No. 6, 82 (1973).

multiple scattering formula, must be replaced by a multi-parameter description where the parameters are the differential inverse mean free paths for the various electron interactions. In terms of transport equations, a Fokker-Planck type equation is replaced by a Boltzmann type integro-differential equation.

We have chosen to solve the Boltzmann equation for the electron flux - from this flux, other quantities of interest may be obtained, e.g., the photoemission yields. In the brief time allotted, this work was made possible by the extensive amount of work previously carried out by Strickland on electron transport in gases.[6] We have borrowed coding from that work wherever possible. Nevertheless, extensive code development was required. Coding, together with acquisition of needed atomic data, consumed the major portion of time available. In spite of this, a considerable number of results will be presented in this report. A word of caution must be given. The results are the first of their kind and have not been critically tested against measurements nor can they be critically tested against results of other existing methods. Furthermore, at this time, we do not know how sensitive the results are to gridding, uncertainties in cross section, etc. Fortunately, a sensitivity study is now underway as well as a comparison with available data under Defense Nuclear Agency (DNA) sponsorship.

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[6] D. J. Strickland, D. L. Book, T. P. Coffey, and J. A. Fedder, J. Geophys. Res., 81, 2755 (1976).

We have examined three materials – aluminum, aluminum oxide, and silicon dioxide, all of which were mutually agreed upon by SAI, RADC, and DNA. Back photoemission yields are presented in this report for these materials. For aluminum, an extensive series of runs was made. In particular, results were obtained for a series of narrow Gaussian photon distributions from 0.5 to 10 keV and for blackbody spectra over a temperature range from 1 to 10 keV. Where comparisons could be made with POEM, the results of this work were found to be higher, but within reasonable agreement.

An exploding wire spectrum from a recent Physics International report was considered for obtaining results for all three materials. The total back yield was found to be sensitive to the material with aluminum providing the highest value and silicon dioxide the lowest.

Section 2

METHOD OF SOLUTION

To properly model the transport of electrons over an energy range which extends below ~1 keV, a single scattering description is required. This entails consideration of all important scattering and loss mechanisms on an individual basis. One can choose to either use a single scattering Monte Carlo approach or solve a Boltzmann equation in its integro-differential form. The latter approach has been chosen here and is based on the earlier work by Strickland, et al.,[6] for electron transport in gases. In this section, we present the transport equation, list the important photon and electron processes, give the matrix representation to the transport equation, and mention how the equation is solved. The discussion will be brief with emphasis placed on publications and reports where more details may be found.

The Boltzmann equation in its integro-differential form is:

$$\mu \frac{d\phi}{dx}(x,E,\mu) = -K_T(E)\phi(x,E,\mu) + \int_{4\pi} d\Omega' \int_{E'>E} dE' \sum_{\ell} K_{\ell}(E,E',\Theta)\phi(x,E',\mu') + P(x,E,\mu) \qquad (1)$$

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[6] D. J. Strickland, D. L. Book, T. P. Coffey, and J. A. Fedder, J. Geophys. Res., 81, 2755, 1976.

The terms are:

- x - depth in cm,
- E - energy in eV,
- μ - cosine of pitch angle with respect to back surface normal,
- Θ - scattering angle,
- K_T - total inverse mean free path (IMFP) in cm^{-1},
- K_ℓ - differential inverse mean free path (DIMFP) for ℓ^{th} process in $cm^{-1}ev^{-1}sr^{-1}$,
- ϕ - electron flux in electrons/cm^2-sec-ev-sr,
- P - electron volume production rate in electrons/cm^3-sec-ev-sr.

One spatial (x) and two velocity (represented by E and μ) variables are considered of the six possible phase space variables. The equation is thus one-dimensional with azimuthal symmetry about the surface normal and is appropriate to broad uniform photon sources normally incident on a material. No restrictions are placed on the description of scattering and energy loss in equation (1). In particular, scattering through any angle, discrete energy loss, and production of secondary electrons are permitted.

The electron volume production rate P contains electrons for the following photon processes:

(1) The photoelectric effect,

(2) Compton scattering, and

(3) Auger emission.

The incident photon spectrum is allowed to be attenuated in the calculations and thus leads to the depth dependence in P expressed in equation (1). An angular dependence given by $1-aP_2(\cos\theta)$ is assigned to the photoelectrons[7] where P_2 is the second Legendre polynomial and θ is the emission angle with respect to the incident photon direction. In this work, the parameter a was set to unity. Isotropic angular dependence is assumed for Auger emission. The dependence for Compton electrons comes from the standard Compton expression — the Klein-Nishina formula (see Evans[8]). For soft x-ray sources, the electron density inserted into this formula is for the electrons in the conduction and/or valence bands of the material. The particular value used is not important since Compton scattering provides relatively few electrons for soft photon sources. Each Auger feature is given a narrow triangular distribution over five equally spaced grid points in energy.

Electron processes modeled in the DIMFP's are:

(1) Elastic scattering,
(2) Plasmon excitation,
(3) Conduction/valence band ionization,
(4) Inner shell ionization, and
(5) Auger emission.

---

[7] J. W. Cooper and S. T. Manson, Phys. Rev. 177, 157 (1969).

[8] R. D. Evans, The Atomic Nucleus, McGraw-Hill Book Co., New York, New York (1955).

Assumptions concerning each process and the corresponding form of the DIMFP may be found in the 1977 RADC final report on x-ray photoemission.[9] Briefly, elastic scattering is permitted through an angle of 180^{o}, plasmon excitation is assumed to be a discrete energy loss process with no change in direction of the incident electron, the ionization processes describe both energy loss of the incident electron and secondary electron production, and, finally, Auger emission is assumed isotropic and triangular in energy as in the case of shell vacancy creation by photons. Angular dependences assigned to degraded primaries and secondaries in the ionization process are based on the laws of energy and momentum conservation.

Choosing a discrete set of energy and angular points, the Boltzmann equation may be transformed into the following matrix equation:

$$\mu_i \frac{d\phi_{ni}(x)}{dx} = \sum_{m \le n} \sum_{j} R_{nmij} \, \phi_{mj}(x) + P_{ni}(x) \qquad (2)$$

where indices n and m refer to energy and i and j refer to pitch angle. The index m does not exceed n in value since electrons cannot gain energy in our formulation. For details on the form of the matrix elements, see Strickland,

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[9] W. L. Chadsey, B. L. Beers, V. W. Pine, D. J. Strickland, and C. W. Wilson, "X-Ray Photoemission; X-Ray Dose Enhancement," RADC Final Report (January 1977).

et al.,[6] and the RADC x-ray photoemission final report.[9] It is convenient to define a new source term given by

$$S_{ni}(x) = \sum_{m<n} \sum_{j} R_{nmij}\, \phi_{mj} + P_{ni}(x) \quad . \qquad (3)$$

Equation (2) is now

$$\mu_i \frac{d\phi_{ni}(x)}{dx} = \sum_{j} R_{nnij}\, \phi_{nj}(x) + S_{ni}(x) \qquad (4)$$

or without the explicit appearance of subscript n,

$$\mu_i \frac{d\phi_i(x)}{dx} = \sum_{j} R_{ij}\, \phi_j(x) + S_i(x) \quad . \qquad (5)$$

This equation is solved by an eigenvalue method, one energy at a time, beginning with the highest energy.[6]

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[6] D. J. Strickland, D. L. Book, T. P. Coffey, and J. A. Fedder, J. Geophy. Res., 81, 2755 (1976).

[9] W. L. Chadsey, B. L. Beers, V. W. Pine, D. J. Strickland, and C. W. Wilson, "X-Ray Photoemission; X-Ray Dose Enhancement," RADC Final Report (January 1977).

Section 3

CODE DEVELOPMENT

The following codes are required in this work for obtaining photoemission characteristics of materials:

(1) a source code,

(2) a matrix code, and

(3) a Boltzmann matrix equation solving code.

The source code generates the production rate $P(x,E,\mu)$ for a given normally incident photon source. The matrix code generates the matrix elements R_{nmij} by carrying out detailed integrations of DIMFP's over energy and angle. Finally, the Boltzmann matrix equation solving code obtains the electron flux $\phi(x,E,\mu)$ for the given outputs of the first two codes. Given the solution ϕ, this code further performs various integrations over x, E, and μ to obtain such quantities as differential and total yields, currents, and dose profiles.

The major part of the work performed was directed to developing the above codes. The source code is totally new whereas the matrix and Boltzmann codes are modified versions of codes used for electron transport in gases. Only minor modifications were needed on the Boltzmann code whereas an essentially new code was developed for obtaining the required matrix.

Following the basic development of these codes, further changes have recently been made so that the three codes may be run as multisteps in a single job. This has significantly increased efficiency in making production runs. A control statement program is now being used which does file manipulation and allows for new multistep runs by merely changing a few selected control and data statements.

Section 4

ATOMIC DATA

The three materials which were investigated are aluminum (Aℓ), aluminum oxide ($A\ell_2O_3$), and silicon dioxide (SiO_2). In this section, the photoabsorption cross sections, Auger yields, and IMFP's used in the calculations are presented for these materials.

The energy levels considered for each material are designated in Tables 1-3. The energies assigned to the valance bands in $A\ell_2O_3$ and SiO_2 were taken from ORNL tabulations.[10,11] Minor shifts that occur in inner shell binding energies in going from the atomic species (Aℓ, Si, O) to the molecular species ($A\ell_2O_3$, SiO_2) have been ignored.

Information pertaining to Auger emission is given in Table 4. The description is simple, but adequate to account for conversion of potential energy of inner shell vacancies to kinetic energy of the emitted Auger electrons. For Aℓ and Si, every K shell vacancy is

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[10] J. C. Ashley, C. J. Tung, V. E. Anderson, and R. H. Ritchie, "Inverse Mean Free Path, Stopping Power, CSCA Range, and Straggling in Aluminum and Aluminum Oxide for Electrons of Energy ≤10 keV," AFCRL-TR-75-0583 (December 1975).

[11] C. J. Tung, J. C. Ashley, V. E. Anderson, and R. H. Ritchie, "Inverse Mean Free Path, Stopping Power, CSDA Range, and Straggling in Silicon and Silicon Dioxide for Electrons of Energy ≤10 keV," Report No. RADC-TR-76-125 (1976).

TABLE 1. ENERGY LEVELS FOR ALUMINUM

LEVEL DESIGNATION	ENERGY (keV)
Conduction Band	0 - 0.011
L_{23}	0.073
L_1	0.114
K	1.56

TABLE 2. ENERGY LEVELS FOR ALUMINUM OXIDE

LEVEL DESIGNATION	ENERGY (keV)
Valance Bands	$\left\{\begin{matrix} 0.009 \\ 0.029 \end{matrix}\right\}$
$A\ell(L_{23})$	0.073
$A\ell(L_1)$	0.114
O(K)	0.533
$A\ell(K)$	1.56

TABLE 3. ENERGY LEVELS FOR SILICON DIOXIDE

LEVEL DESIGNATION	ENERGY (keV)
Valance Bands	$\left\{\begin{matrix} 0.0094 \\ 0.024 \end{matrix}\right\}$
$Si(L_{23})$	0.10
$Si(L_1)$	0.151
O(K)	0.533
Si(K)	1.84

TABLE 4. AUGER ENERGIES AND YIELDS FOR Aℓ, Si, AND O

VACANCY	AUGER ENERGY (keV)	YIELD
Aℓ(K)	1.4	0.95
Aℓ(L)	0.07	1.0
Si(K)	1.6	0.94
Si(L)	0.08	1.0
O(K)	0.50	1.0

assumed to first lead to a KLL Auger electron with probability given by the Auger yield. This leads to two L shell vacancies and, in turn, to two further Auger electrons with assumed probability of unity. For oxygen, only KLL Auger electrons are treated. Intra L-shell emission occurs at $\lesssim$20 ev, below the region of interest in this work. Useful references to the Auger process for low-Z atoms are, e.g., McGuire,[12] Yasko and Whitmoyer,[13] and Walters and Bhalla.[14]

The photoabsorption cross sections appear in Figures 1-3 and were taken from Biggs and Lighthill.[15] No attempt was made to separate the L shell cross section into its L_1 and L_{23} components. The L shell binding energy was taken to be that for the L_{23} shell.

The IMFP's for electron processes listed in the previous section are shown in Figures 4-6. All inelastic IMFP's come from the work of the Health Physics Group at

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[12] E. J. McGuire, Phys. Rev. 185, 1 (1969).

[13] R. N. Yasko and R. D. Whitmoyer, J. Vac. Sci. Tech. 8, 733 (1972).

[14] D. L. Walters and C. P. Bhalla, Phys. Rev. A, 4, 2164 (1971).

[15] F. Biggs and R. Lighthill, Report #SC-RR-71-0507, Sandi Laboratories (1971).

ORNL.[10,11,16] The elastic IMFP's are based on the screened Rutherford cross section with the screening parameter of Molieré.[17] Below 0.1 keV, the elastic IMFP is allowed to become constant in a manner similar to that observed for N_2, O_2, and O.[18,19]

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[10] J. C. Ashley, C. J. Tung, V. E. Anderson, and R. H. Ritchie, "Inverse Mean Free Path, Stopping Power, CSDA Range, and Straggling in Aluminum and Aluminum Oxide for Electrons of Energy ≤10 keV," AFCRL-TR-75-0583 (December 1975).

[11] C. J. Tung, J. C. Ashley, V. E. Anderson, and R. H. Ritchie, "Inverse Mean Free Path, Stopping Power, CSDA Range, and Straggling in Silicon and Silicon Dioxide for Electrons of Energy ≤10 keV," Report No. RADC-TR-76-125 (1976).

[16] C. J. Tung, R. H. Ritchie, J. C. Ashley, and V. E. Anderson, "Inelastic Interacations of Swift Electrons in Solids," Report No. ORNL-TM-5188 (1976).

[17] G. Molieré, Z. Naturforsch, A3, 78 (1948).

[18] J. B. Fisk, Phys. Rev. 49, 167 (1936).

[19] G. Sunshine, B. B. Aubrey, and B. Bederson, Phys. Rev. 154, 1 (1967).

Section 5

RESULTS

The basic quantity calculated in this work is the electron flux $\phi(x,E,\mu)$. This gives the energy and angular dependence of photoelectrons throughout the slab of material being considered. The quantity of primary interest here is the cumulative back yield which is related to ϕ by

$$Y_B(E) = 2\pi \int_E^{E_{max}} dE' \int_{-1}^{0} d\mu\mu\phi(x=0,E',\mu) \Big/ F \qquad (6)$$

(electrons/photon above electron energy E)

where F is the total number of incident photons. The differential yield in energy $\frac{dY_B}{dE}$ is also of interest:

$$\frac{dY_B(E)}{dE} = 2\pi \int_{-1}^{0} d\mu\mu\phi(x=0,E,\mu) \Big/ F \qquad (7)$$

(electrons/photon-keV).

The emphasis in this section will be on these two quantities.

5.1 PHOTOEMISSION FROM Aℓ FOR GAUSSIAN SOURCES

The purpose in considering photon distributions which are Gaussian in energy is for the simulation of line sources. The simulation is effective provided the distribution is limited to an energy range over which the yield varies by only a few percent. This was achieved by using the Gaussian formula

$$F(E) = \exp[(E-E_o)/aE_o]^2$$

with a $\lesssim 0.1$. For most cases, an a-value of 0.05 was used. Smaller values were also considered, specifically, for energies close to the K-edge energy in aluminum.

Figure 7 gives the calculated back emission yield for Aℓ versus Gaussian photon energy E_o over a range from 0.5 to 10 keV. Electron emission was calculated down to $\sim$0.1 keV. Several other results are shown in the figure for comparison. Measurements are provided by Eliseenko, et al.[20] and Savinov, et al.[21] Transport results are shown from the codes POEM[22] and QUICKE2[4] and were obtained by running these codes specifically for this comparison.

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[4] T. A. Dellin and C. J. MacCallum, IEEE Trans. Nuc. Sci., NS-20, No. 6, 91 (1973).

[20] L. G. Eliseenko, V. N. Shehemelev, and M. A. Runsh, Sov. Phys. - Tech. Phys. 13, 122 (1968).

[21] E. P. Savinov, A. P. Lukirskii, and Yu. F. Shepelev, Sov. Phys. - Sov. State 6, 2624 (1965).

[22] W. L. Chadsey and C. W. Wilson, "X-Ray Photoemission," Report No. HDL-CR-75-138-1 (1975).

Finally, the empirical result of Schaefer[23] is shown which is based on the sum of products of the photon absorption coefficient at E_o and the penetration depths of the various types of electrons produced.

The agreement with the other available yields above the aluminum K-edge is encouraging considering the limited testing so far performed on the newly developed codes. The difference between our results and the measurements by Savinov, et al.[21] below the K-edge remains to be determined. Based on the recent range calculations by Ashley, et al.,[10] Schaefer's result at low energies will significantly increase using this new information in place of his low energy extrapolated range.

The next several figures serve to provide more detailed information on our results for Gaussian photon sources. Differential back yields [$dY_B(E)/dE$] and cumulative back yields [$Y_B(E)$] are shown in Figures 8-14 for E_o = 0.5, 1.0, 1.4, 1.7, 2.0, 4.0, and 10.0 keV. Table 5 gives the value of $Y_B(E)$ for these E_o values for the lowest electron energy E treated in the calculations (either 0.1 or 0.05 keV). For E_o < 1.56 keV (K-edge energy), the highest energy peak in dY_B/dE is due to L

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[10] J. C. Ashley, C. J. Tung, V. E. Anderson, and R. H. Ritchie, "Inverse Mean Free Path, Stopping Power, CSDA Range, and Straggling in Aluminum and Aluminum Oxide for Electrons of Energy ≤10 keV," Report No. AFCRL-TR-75-0583 (December 1975).

[21] E. P. Savinov, A. P. Lukirskii, and Yu. F. Shepelev, Sov. Phys. - Sov. State <u>6</u>, 2624 (1965).

[23] R. R. Schaefer, J. Appl. Phys. <u>44</u>, 152 (1973).

TABLE 5. CUMULATIVE YIELD Y_B FOR SEVERAL GAUSSIAN SOURCES

GAUSSIAN PEAK ENERGY E_o	Y_B (e/phot)
0.5	2.5×10^{-3}
1.0	9.9×10^{-4}
1.4	8.6×10^{-4}
1.7	7.8×10^{-3}
2.0	5.7×10^{-3}
4.0	2.7×10^{-3}
10.0	1.2×10^{-3}

photoelectrons. The 0.07 keV feature is due to LMM Auger electrons. Starting with Figure 11, E_o is greater than the K-edge energy and results in significant changes in both types of yields. In Figure 11, for example, the peaks in dY_B/dE in order of decreasing energy are due to L-photo-, KLL Auger, K-photo-, and finally, LMM Auger electrons. For photon energies just above the K-edge, the spectra are seen to be dominated by KLL Auger electrons. At E_o = 10 keV, however, Auger electrons provide only a minor contribution with the dominant source coming from K-photoelectrons.

5.2 PHOTOEMISSION FROM Aℓ FOR BLACKBODY SOURCES

We next present results for a series of blackbody spectra incident on Aℓ. Five spectra with temperatures of 1.0, 2.0, 5.0, 7.5, and 10 keV were considered. The yield Y_B is shown in Figure 15, and is tabulated in Table 6, versus temperature in keV. For comparison, available POEM[9] results are also shown and, as with the previous comparison, are found to be below the results of this work. The difference increases with decreasing source temperature, as expected, since sub-kilovolt electrons are becoming increasingly important.

Figures 16-19 provide further information for the results in Figure 15. Shown in each of these figures are $dY_B(E)/dE$ and $Y_B(E)$ versus electron energy E for a different blackbody temperature. The temperatures selected for these results are 1.0, 2.0, 4.0, and 10.0 keV. The differential

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[9] W. L. Chadsey, B. L. Beers, V. W. Pine, D. J. Strickland, and C. W. Wilson, "X-Ray Photoemission; X-Ray Dose Enhancement," RADC Final Report (January 1977).

TABLE 6. CUMULATIVE YIELD Y_B FOR SEVERAL BLACKBODY SOURCES

TEMPERATURE (keV)	Y_B (e/phot) (This work)	Y_B (e/phot) (POEM)
1	2.6×10^{-3}	--
2	2.1×10^{-3}	1.3×10^{-3}
5	1.1×10^{-3}	8.8×10^{-4}
7.5	8.8×10^{-4}	6.4×10^{-4}
10	6.3×10^{-4}	5.0×10^{-4}

yields shown have some noticeable differences compared with those shown in Figures 8-14 for narrow Gaussian photon sources. Here, a broad K-photoelectron continuum typically dominates the spectrum. As before, we observe the KLL and LMM Auger features starting at ∿1.4 and 0.07 keV. With the exception of T=1 keV, photoelectrons, rather than Auger electrons, dominate the photoemission spectrum.

5.3 PHOTOEMISSION FROM Aℓ, $A\ell_2O_3$, and SiO_2 FOR AN EXPLODING WIRE SPECTRUM

The primary goal of work begun under the given DNA/RADC contract is to develop a predictive capability in soft x-ray photoemission for making comparisons with photoemission data and providing physical insight into the photoemission process itself in the DNA sponsored exploding wire radiation program (EWR). As a beginning in the study of photoemission for EWR sources, we have run our transport codes for the photon spectrum shown in Figure 20, which is based on information appearing in a January 1977 Physics International report.[24] The spectra in this report show that ∿50% of the energy resides in the line features occurring at 1.6 and 1.7 keV. The Gaussian feature peaking at 1.65 keV in Figure 20 has been substituted for these lines and itself contains ∿50% of the total energy. One should not necessarily interpret this figure to mean that no photons are present at lower energies for actual wires spectra in the test chamber. We are using data available

[24] K. Nielson, "Exploding Wire Radiation Source Support for Skynet Phenomenology Experiments," Physics International (January 1977).

to us at this time which covers the range from 1.3 to 3.4 keV. Over this range beginning at 3.4 keV, reported cumulative energy distributions reach 100% at 1.6 keV.

The yields dY_B/dE and Y_B for Aℓ and $A\ell_2O_3$ are shown in Figure 21 for the source spectrum in Figure 20. The results for SiO_2 appear in Figure 22. The dominant feature starting at ∿1.4 keV and continuing to lower energies in both spectra in Figure 21 is Auger electron emission arising from Aℓ K-shell vacancies. The dominance by Auger electrons is due to the abundance of photons lying just above the 1.56 keV K-edge of aluminum. The minor contribution above 1.5 keV in both spectra is due to L photoelectrons which weakly reflect the source spectrum. Below 0.2 keV, the spectra rise and peak at 0.07 keV as a result of both K-photoelectron and Auger electron emission. Here the Auger electrons arise from L-shell vacancies in aluminum. The additional feature in the $A\ell_2O_3$ spectrum at 0.5 keV is due to Auger emission arising from K-shell vacancies in oxygen.

Significant differences are seen between photoemission from Aℓ and $A\ell_2O_3$. The most striking difference is in Auger photoemission for the Aℓ KLL transition. We expect the decrease shown in $A\ell_2O_3$ since over the same mean free path distance in either material, the available number of aluminum atoms has decreased by more than a factor of two in $A\ell_2O_3$. We see that the cumulative yield at 0.05 keV is about twice as large for Aℓ.

The photoemission spectrum for SiO_2 in Figure 22 is noticeably different compared to Aℓ and $Aℓ_2O_3$, due primarily to the K-edge of silicon being situated above the 1.65 keV Gaussian feature in the source spectrum. The Si K-edge occurs at 1.84 keV. The primary contribution to the 1.55 keV feature is Si KLL Auger electrons although Si L-photoelectrons arising from the 1.65 keV Gaussian photon feature also contribute. The peak at 1.1 keV is due to O K-photoelectrons, that at 0.5 keV comes from O KLL Auger electrons, and, finally, the low energy feature results from Si K-photoelectrons and Si LMM Auger electrons. Unlike Aℓ or $Aℓ_2O_3$, KLL Auger electrons do not dominate the emission spectrum which is a result of the Si K-edge lying above an important energy region of the source spectrum. For this same reason, SiO_2 has the smallest total yield of the three materials. Its value is 2.1×10^{-3} electrons/photon compared with 7.1×10^{-3} and 3.8×10^{-3} for Aℓ and $Aℓ_2O_3$.

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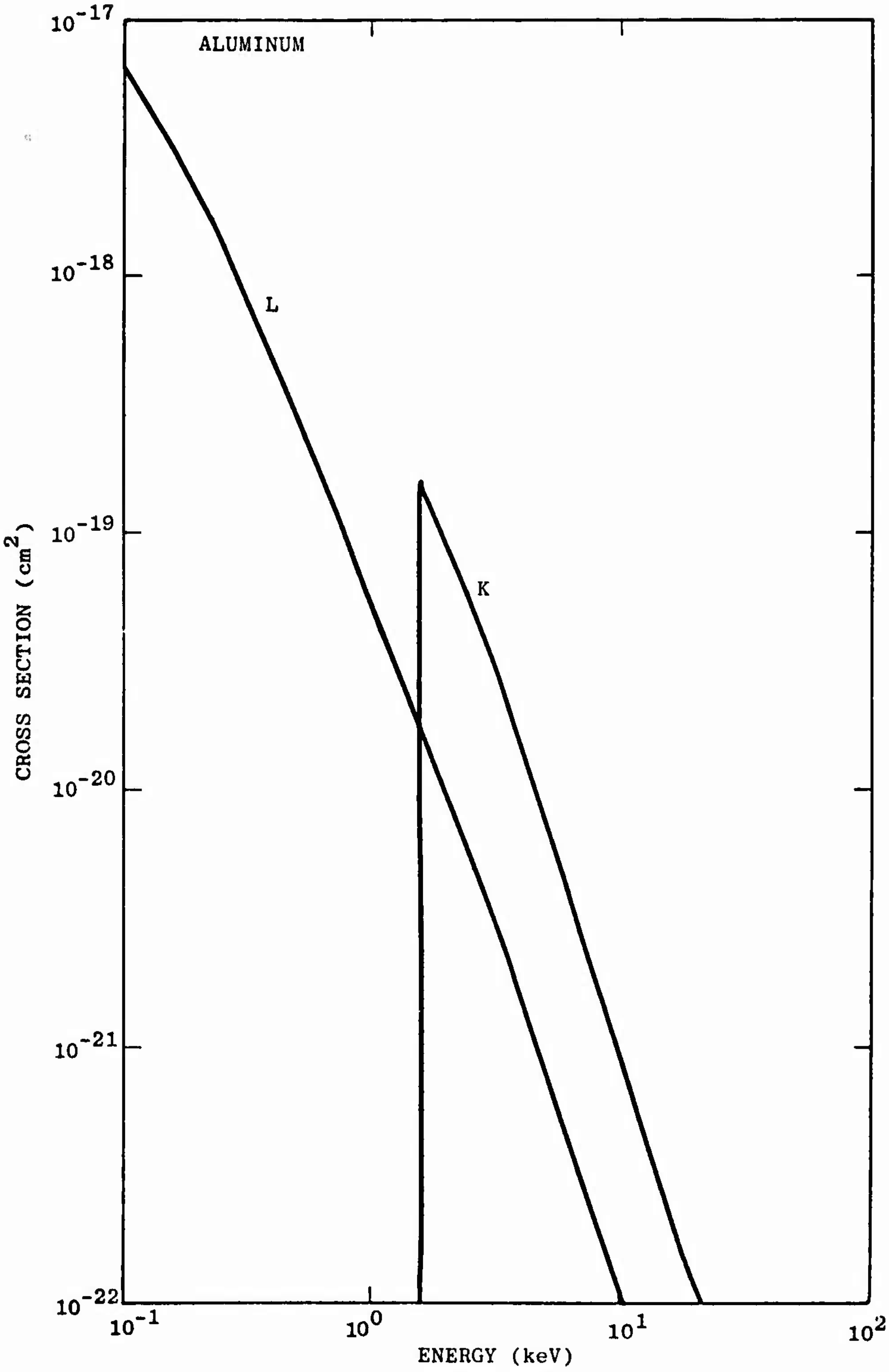

FIGURE 1. Photoabsorption Cross Section for $A\ell$ Taken from Biggs and Lighthill[15]

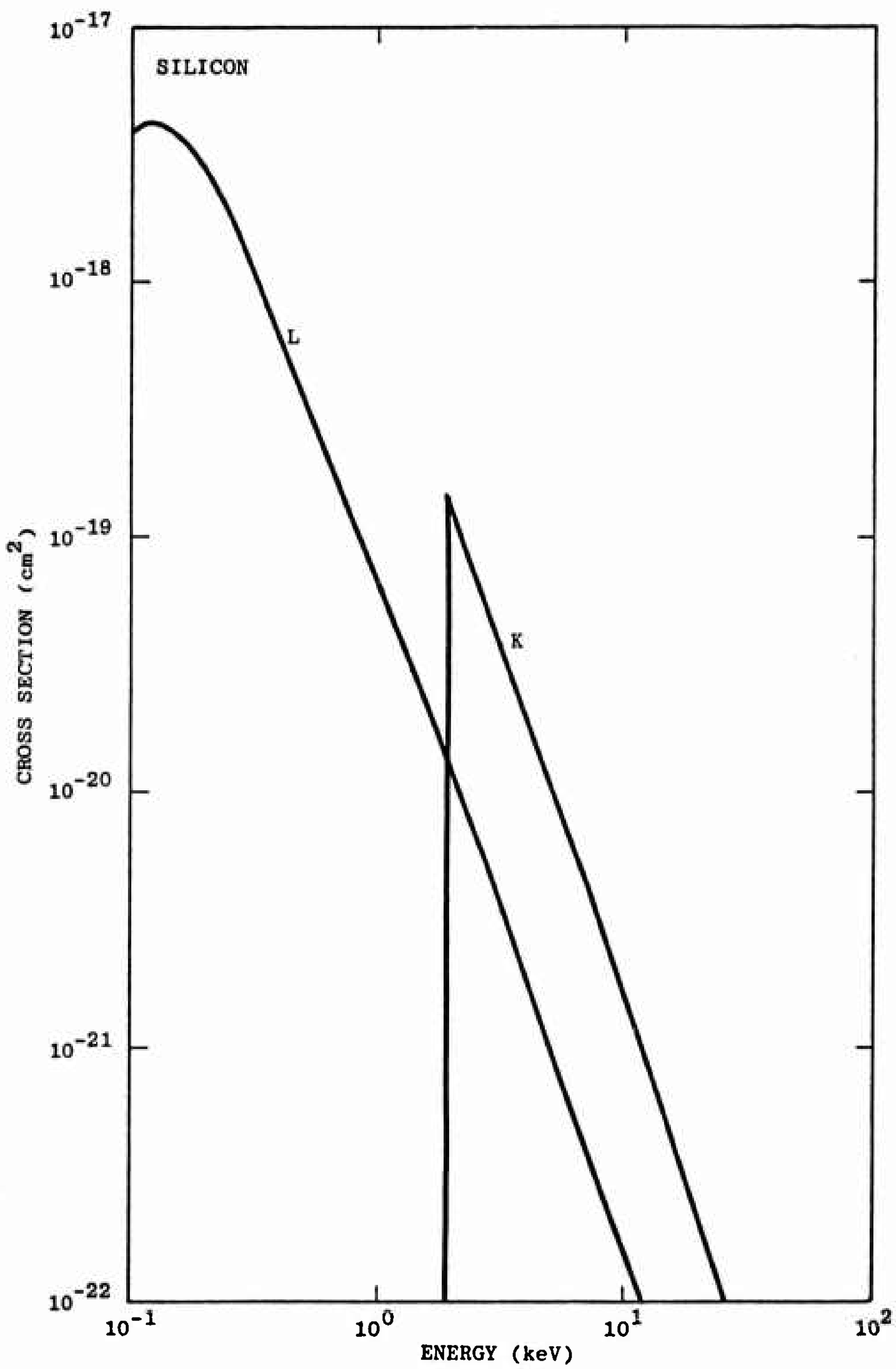

FIGURE 2. Photoabsorption Cross Section for Si Taken from Biggs and Lighthill[15]

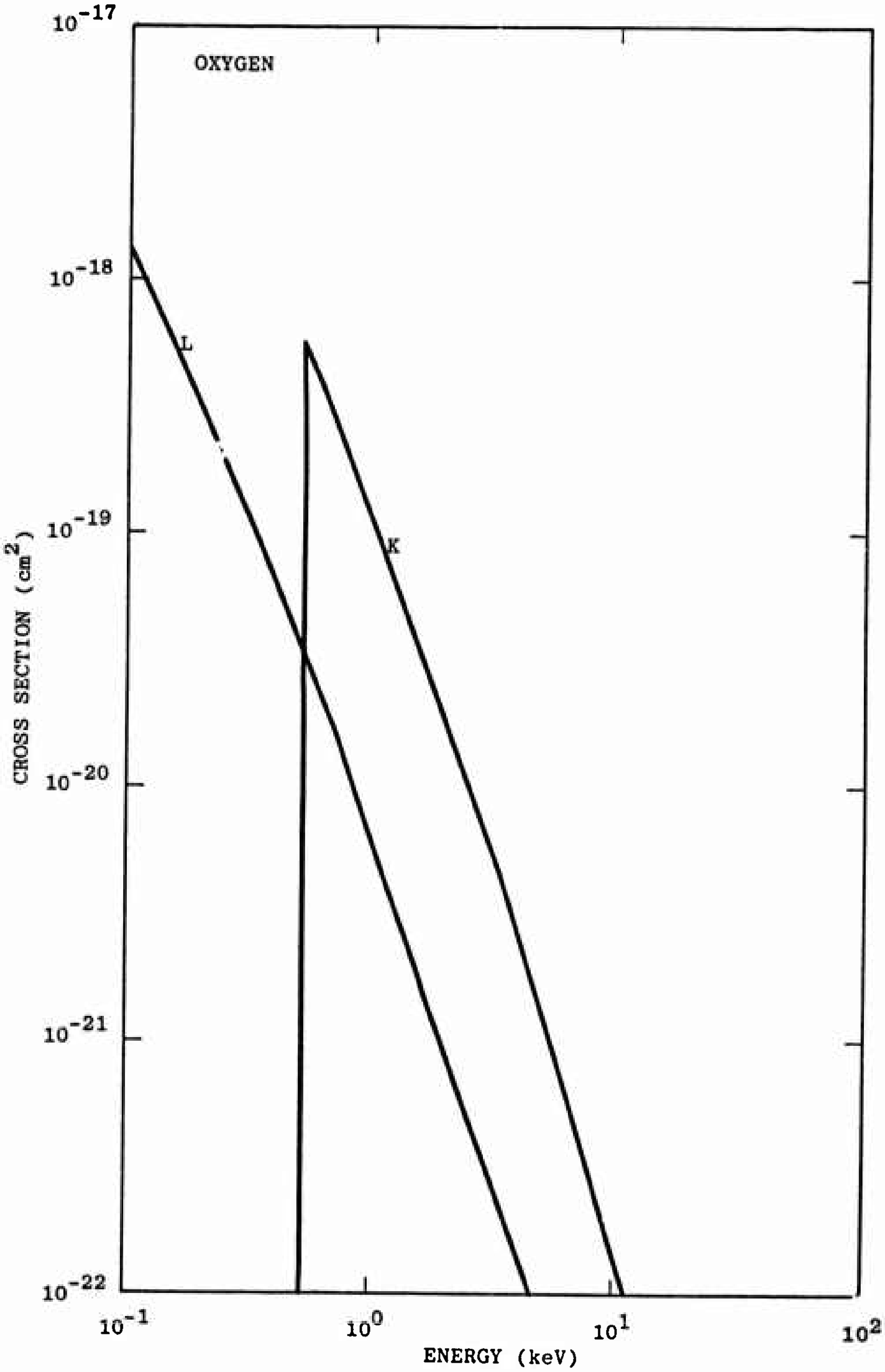

FIGURE 3. Photoabsorption Cross Section for O Taken from Biggs and Lighthill[15]

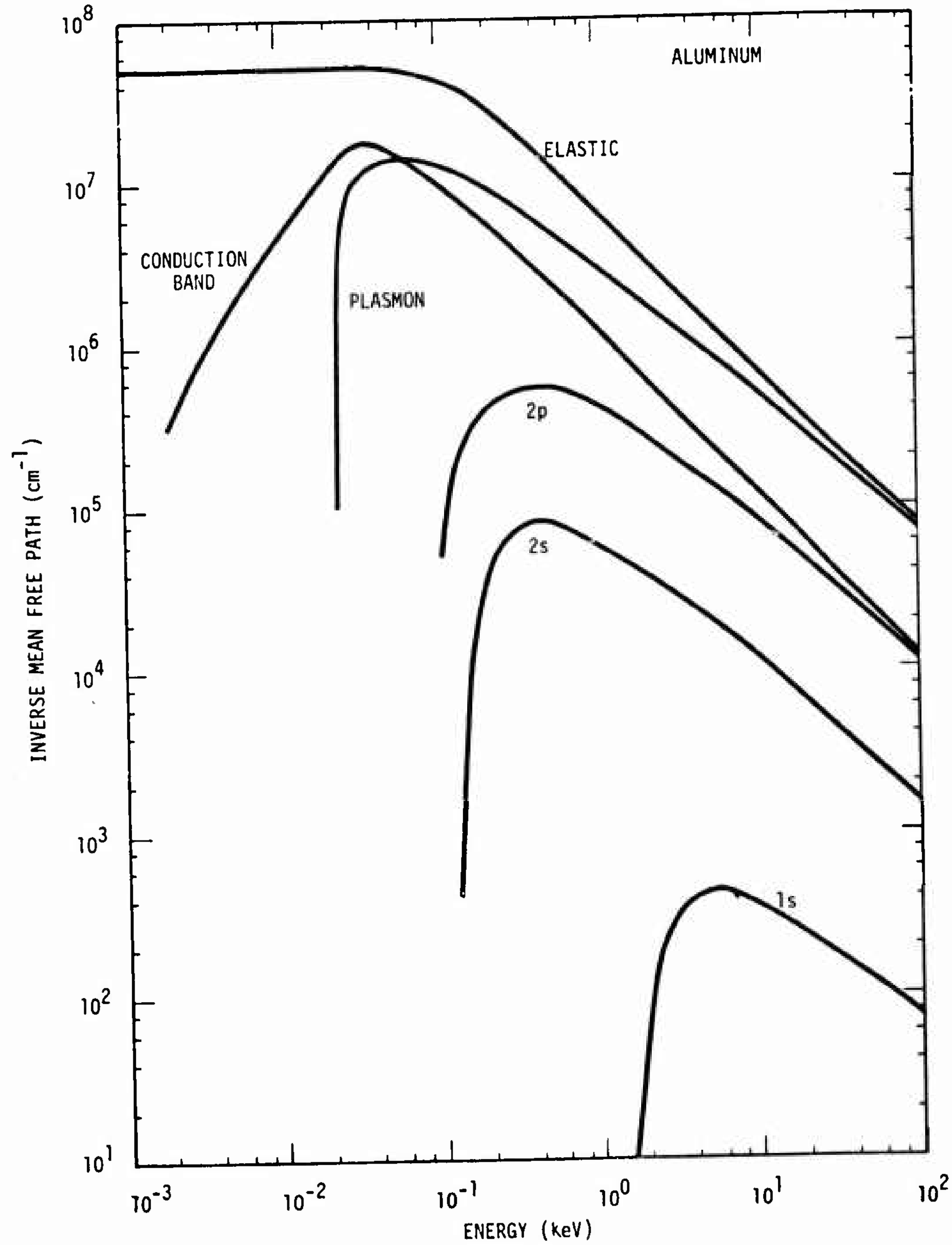

FIGURE 4. IMFP's for Aℓ. Inelastic IMFP's Were Taken from Tung, et al.[16]

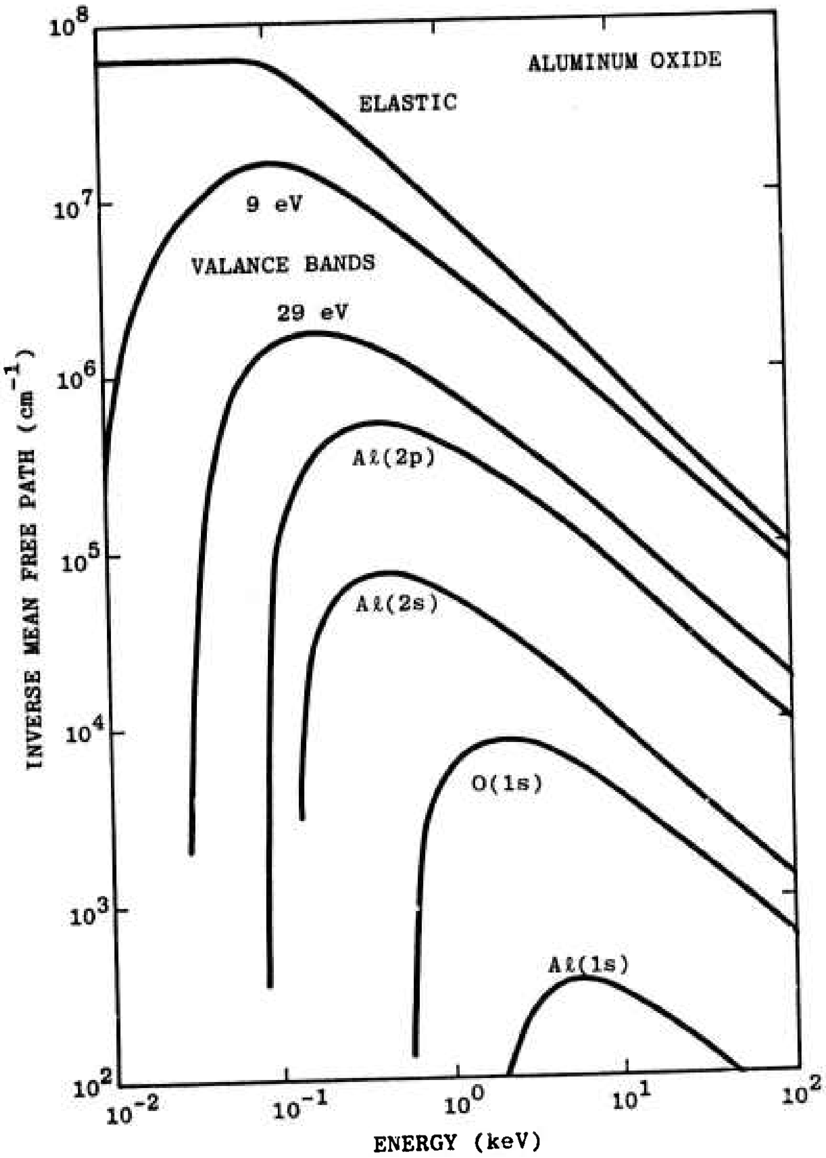

FIGURE 5. IMFP's for $A\ell_2O_3$. Inelastic IMFP's Were Taken from Ashley, et al.[10]

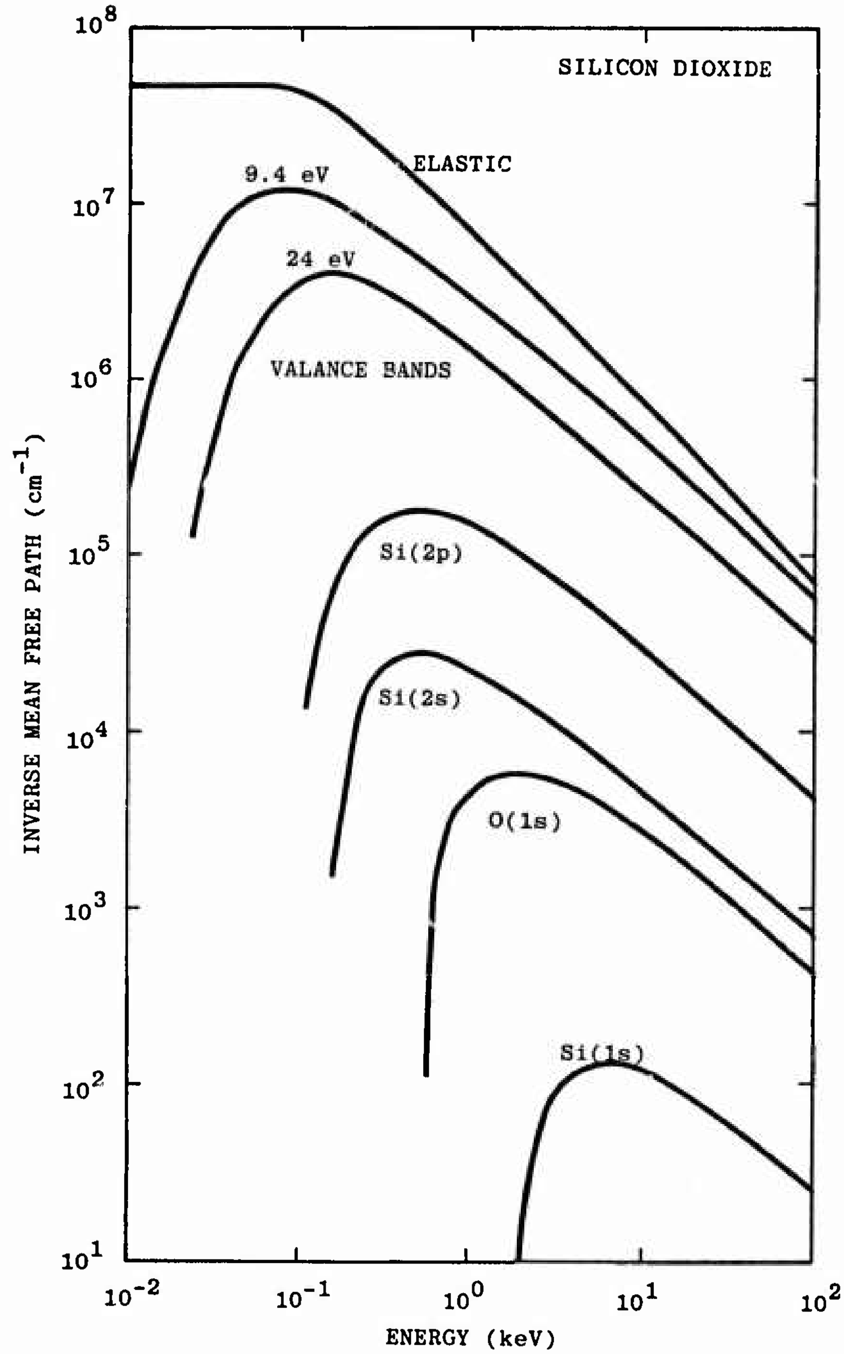

FIGURE 6. IMFP's for SiO_2. Inelastic IMFP's Were Taken from Tung, et al.[11]

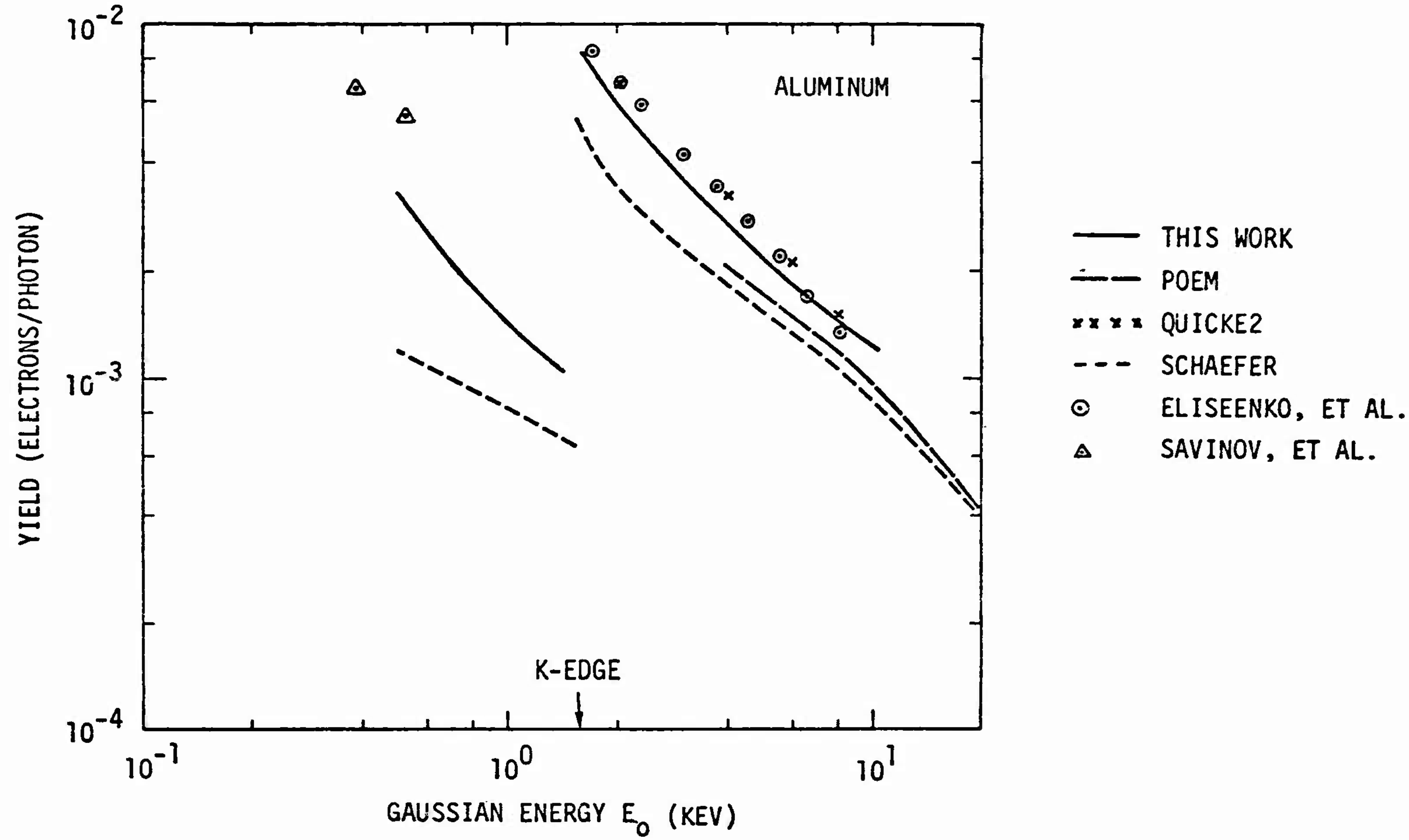

FIGURE 7. Back Yields versus Photon Energy
The Yields from this Work Were Obtained for Narrow Gaussian Photon Distribution

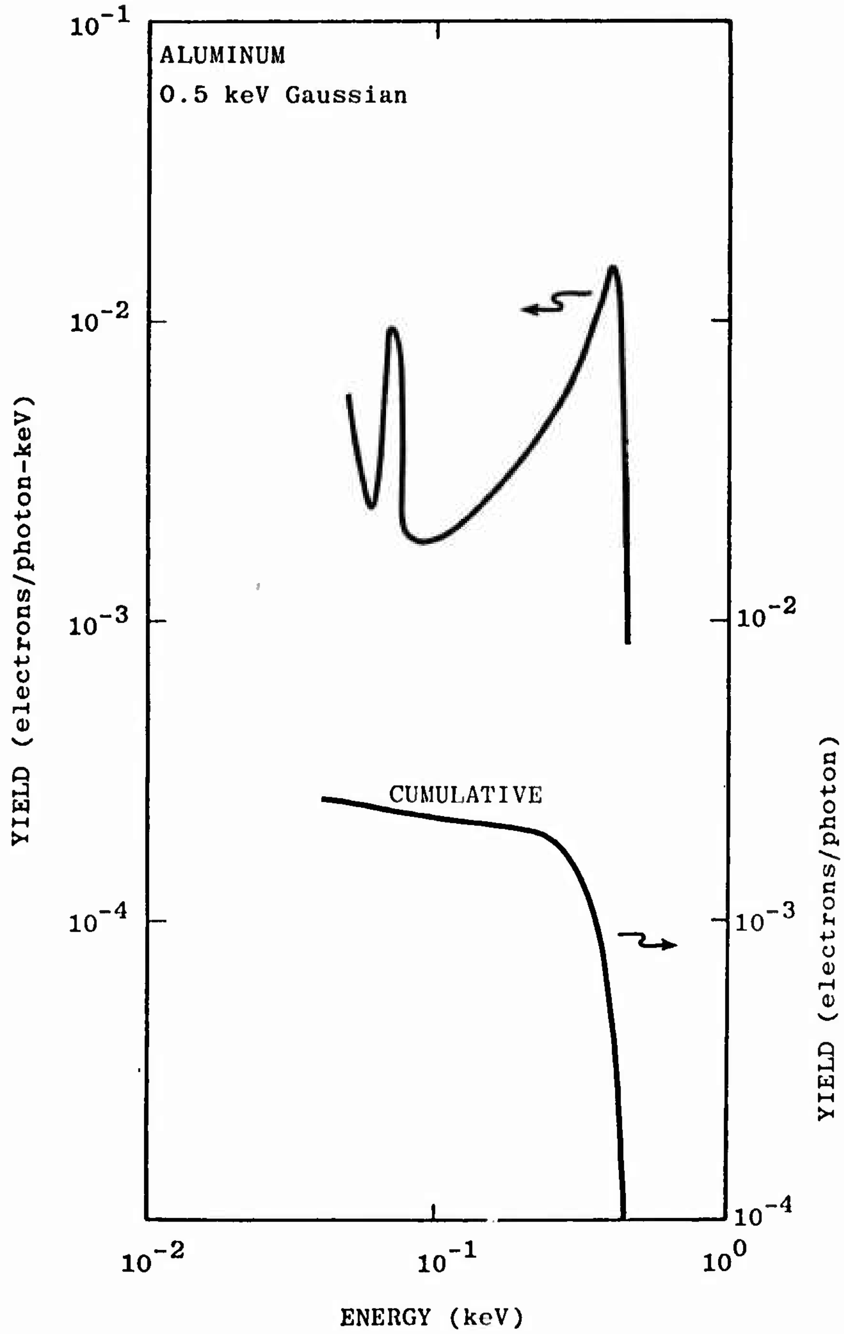

FIGURE 8. Differential and Cumulative Back Yields for Aℓ for a 0.5 keV Gaussian Photon Distribution

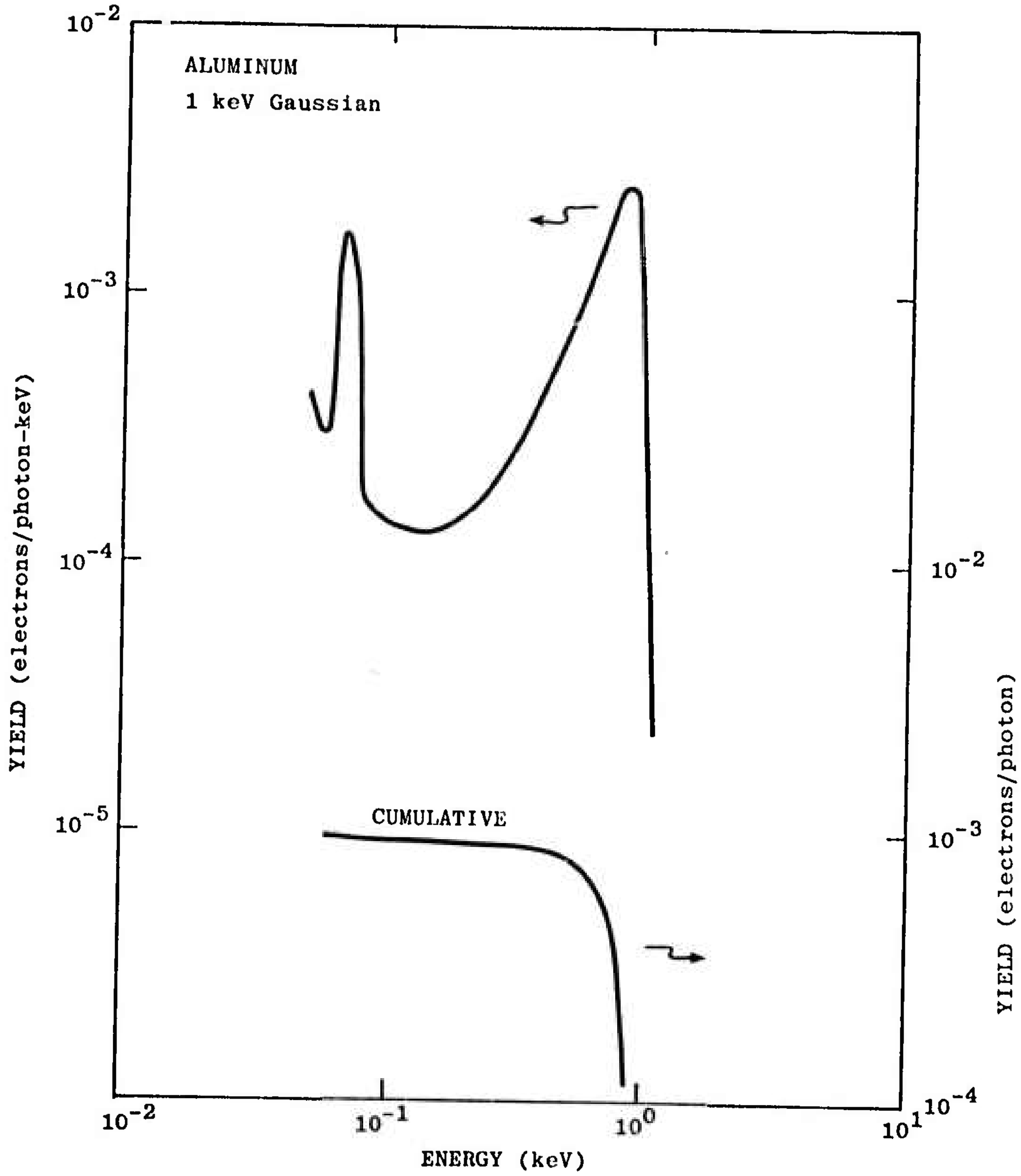

FIGURE 9. Back Yields for a 1.0 keV Gaussian Photon Distribution

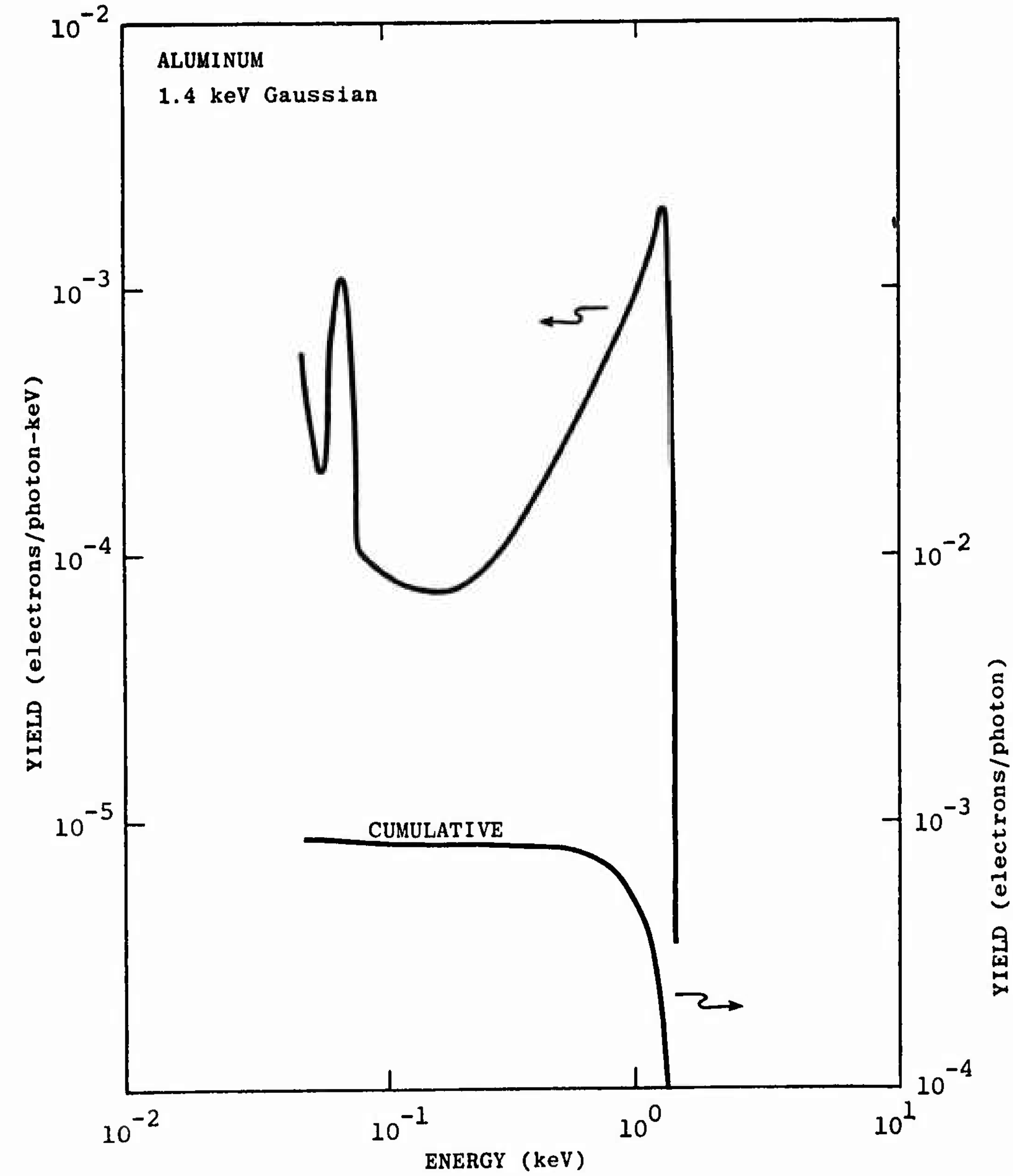

FIGURE 10. Back Yields for a 1.4 keV Gaussian Photon Distribution.

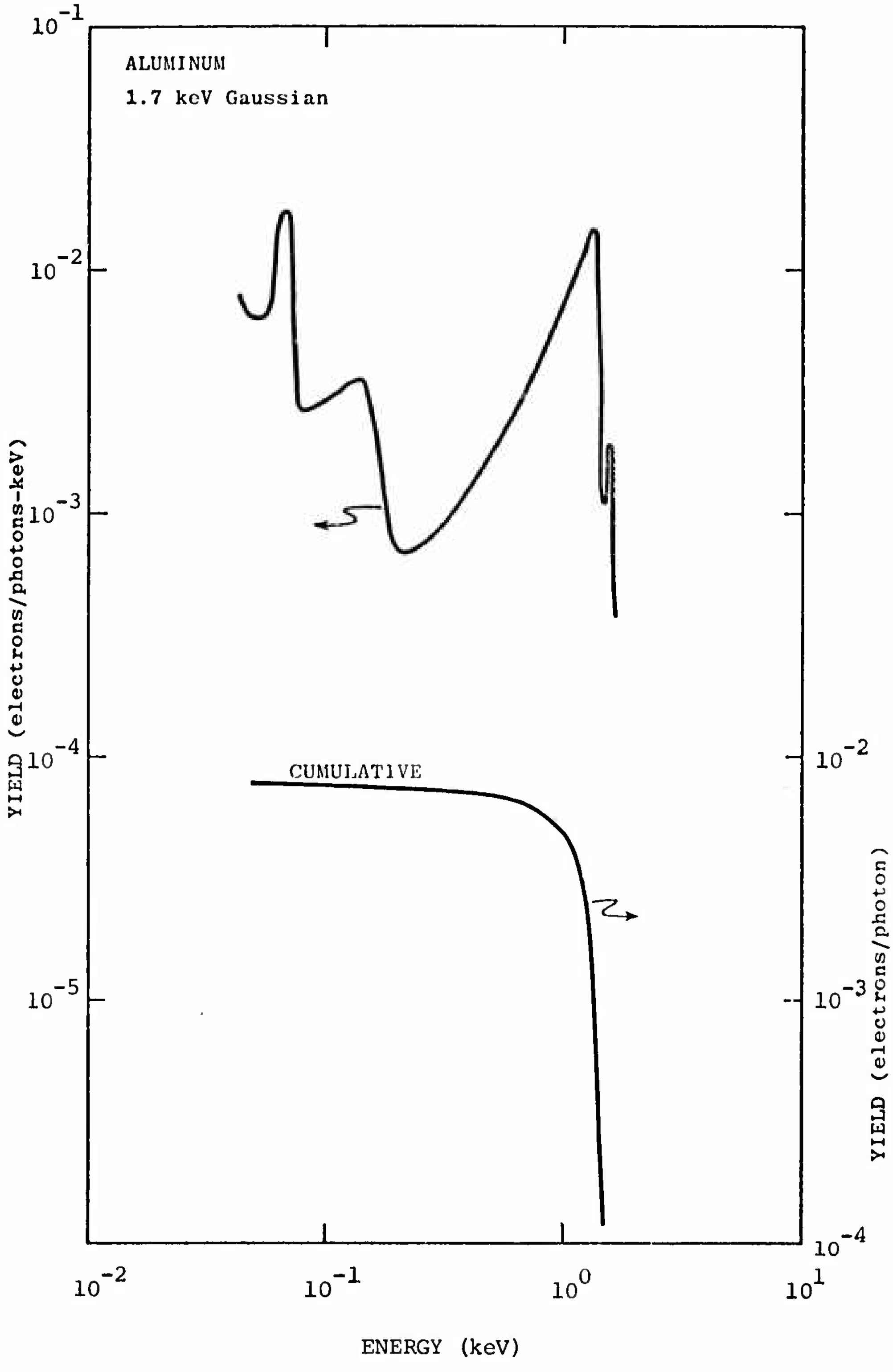

FIGURE 11. Back Yields for a 1.7 keV Gaussian Photon Distribution

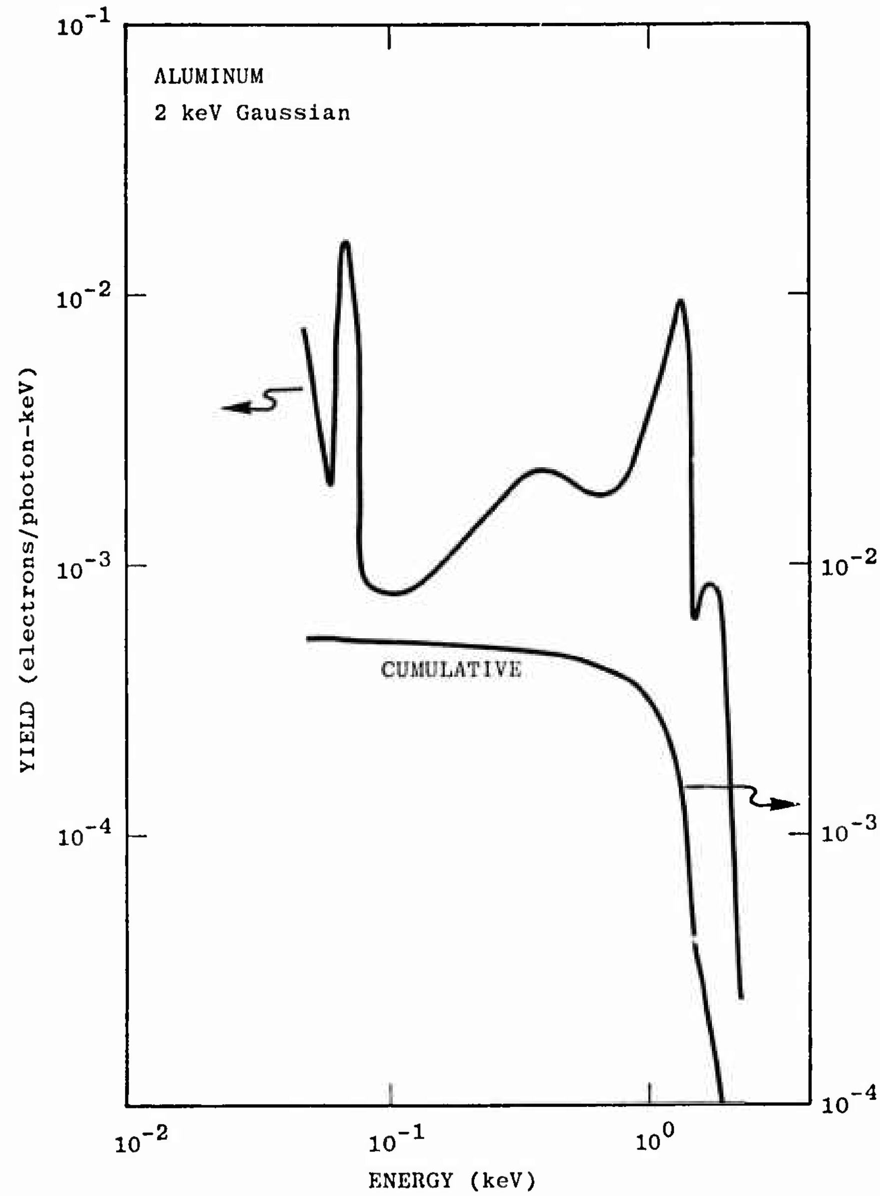

FIGURE 12. Back Yields for a 2 keV Gaussian Photon Distribution

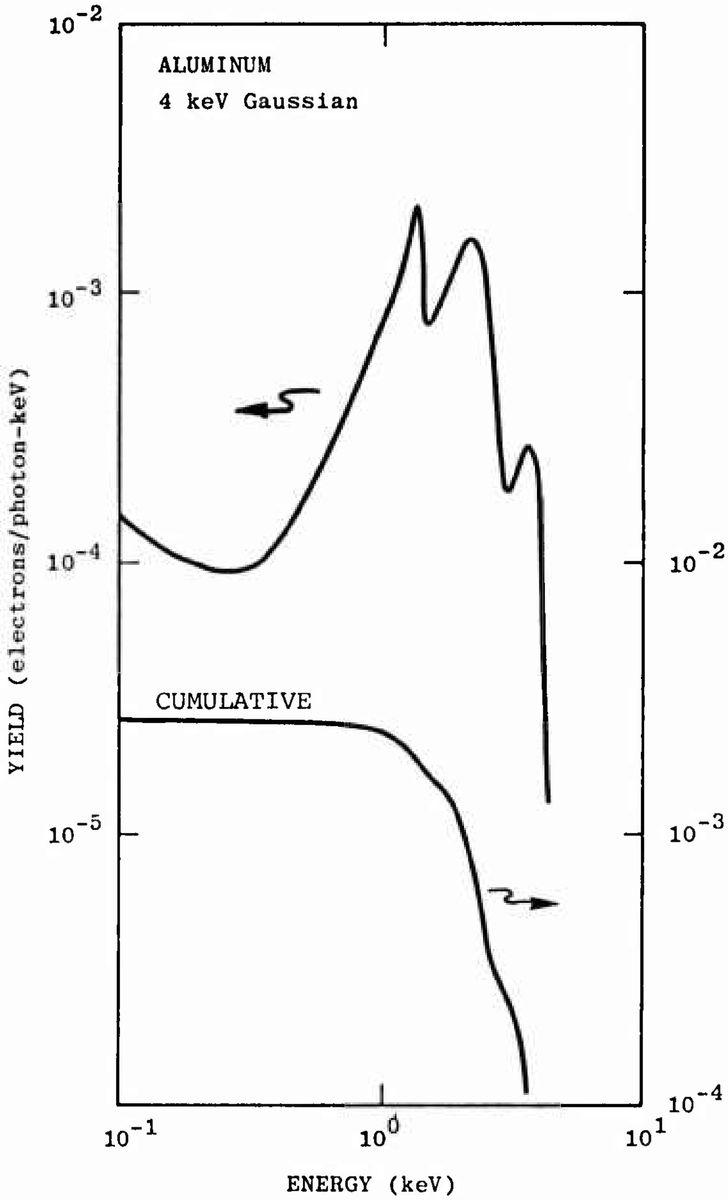

FIGURE 13. Back Yields for a 4 keV Gaussian Photon Distribution

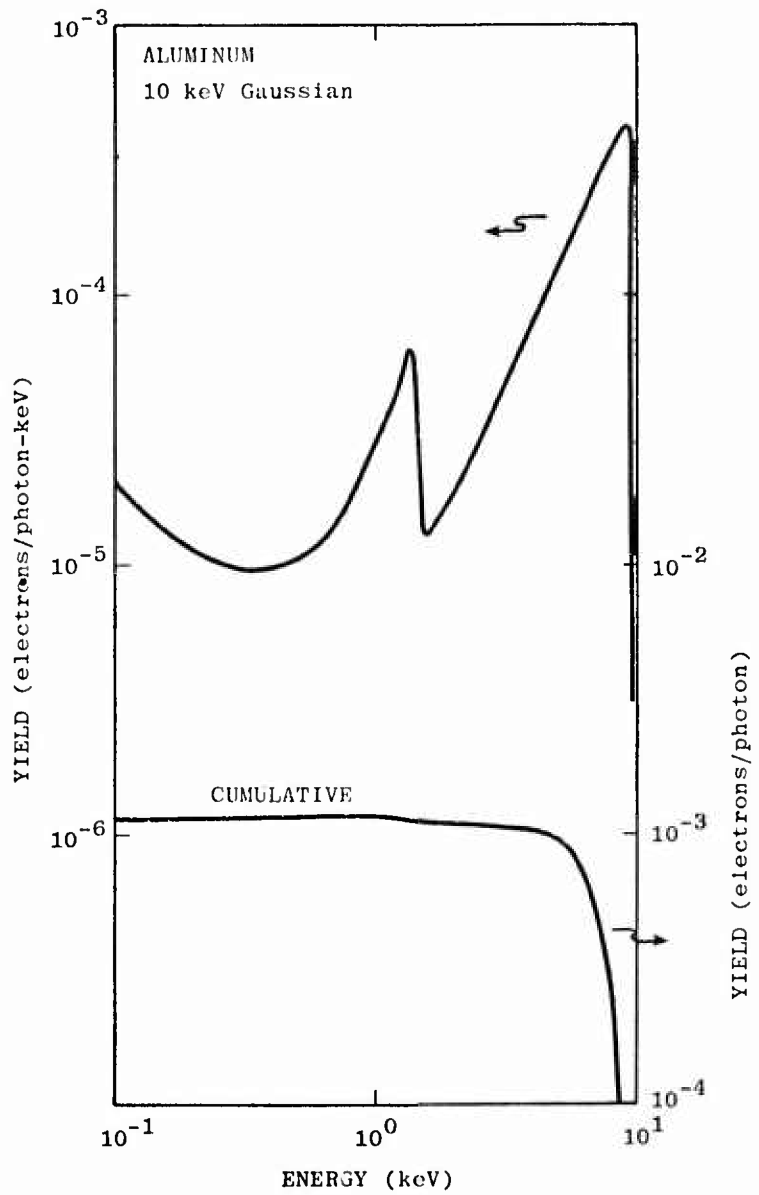

FIGURE 14. Back Yields for a 10 keV Gaussian Photon Distribution

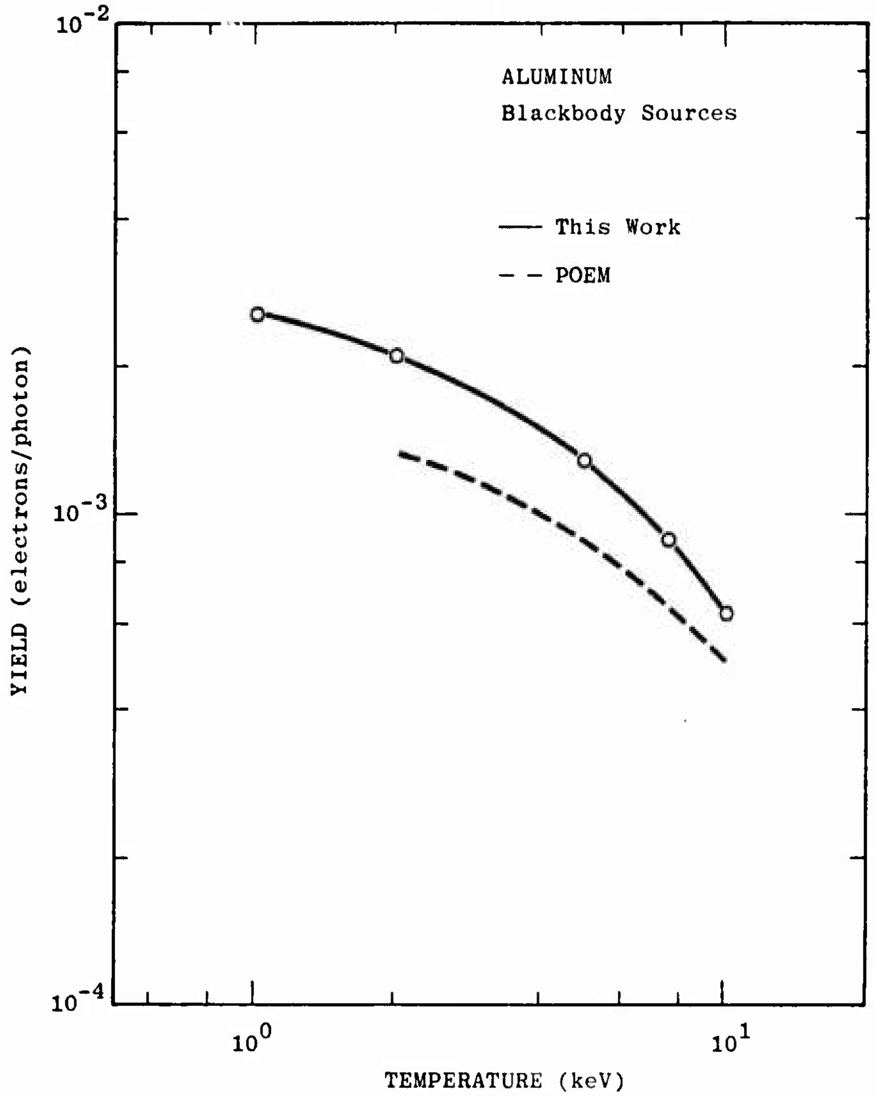

FIGURE 15. Back Yields for Aℓ for Blackbody Spectra.

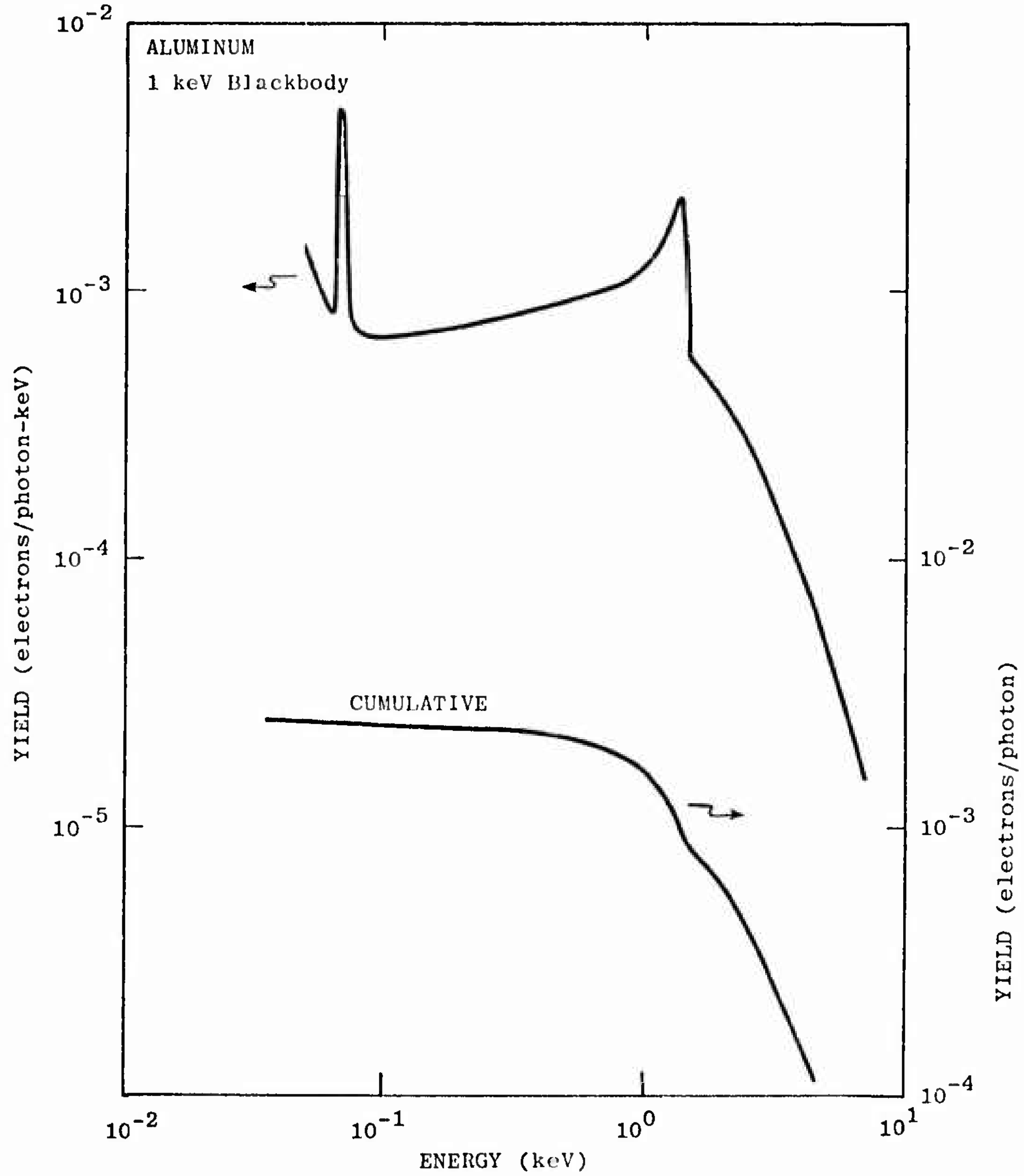

FIGURE 16. Differential and Cumulative Back Yields for Aℓ for a 1 keV Blackbody Spectrum

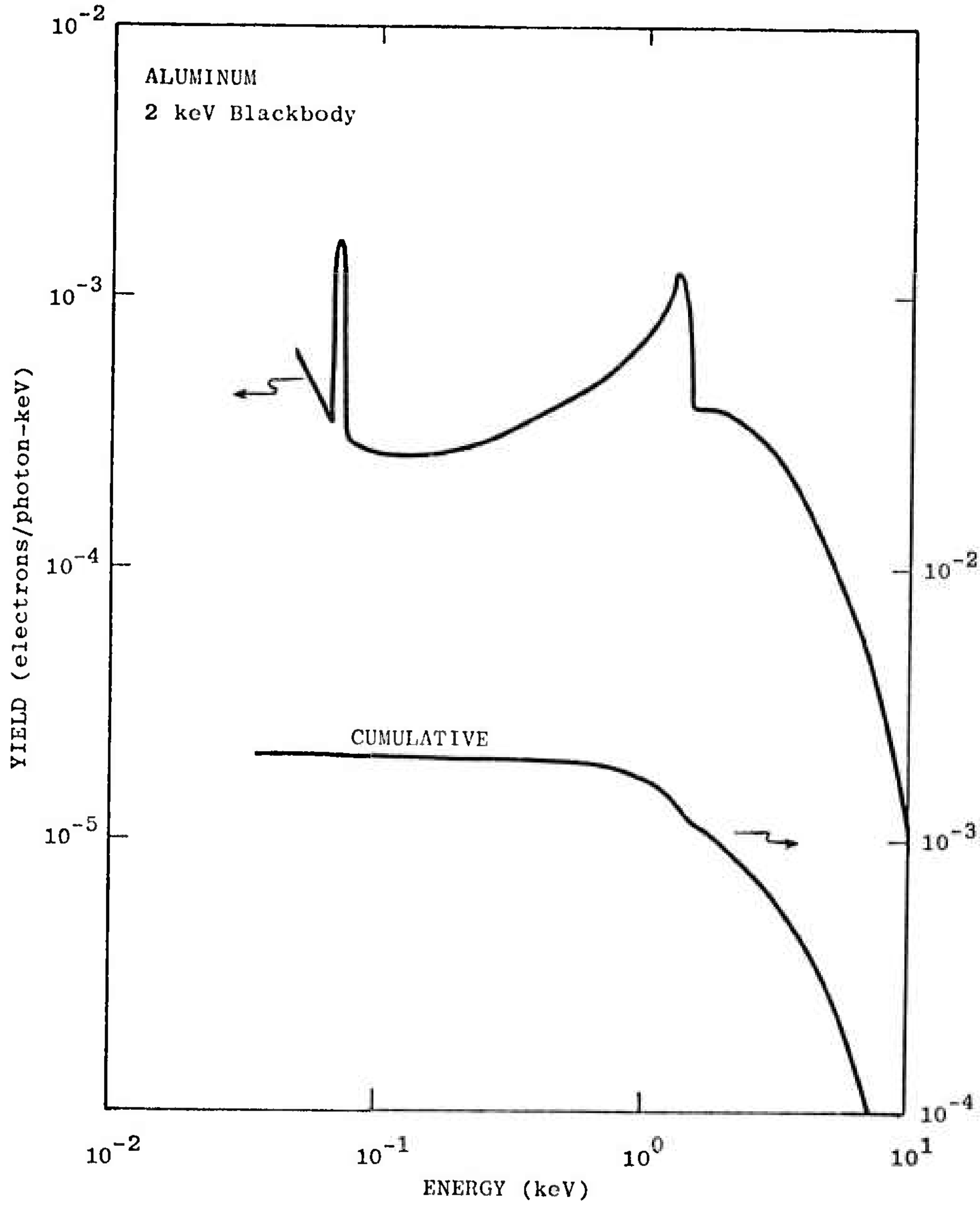

FIGURE 17. Back Yields for a 2 keV Blackbody Spectrum

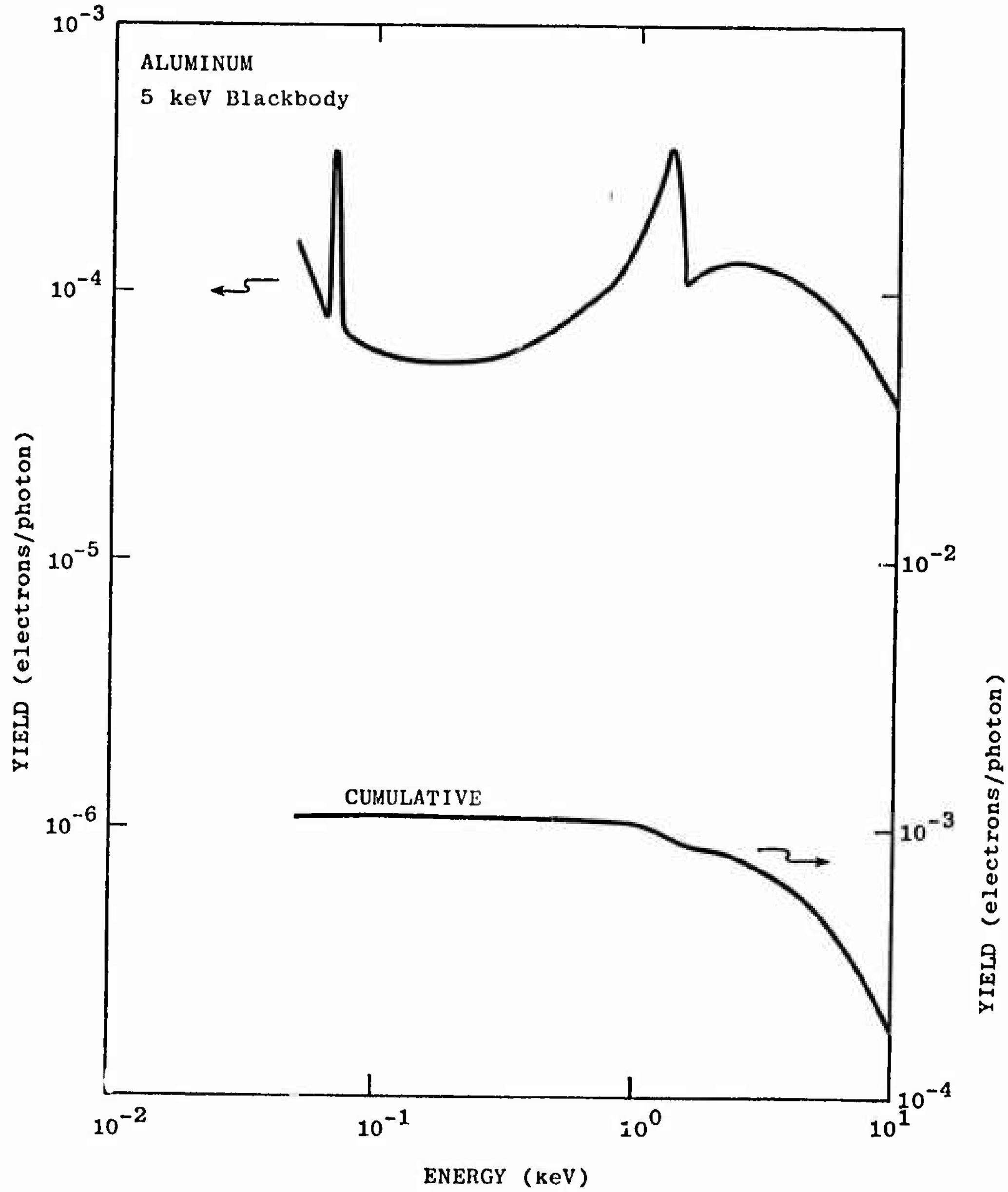

FIGURE 18. Back Yields for a 5 keV Blackbody Spectrum

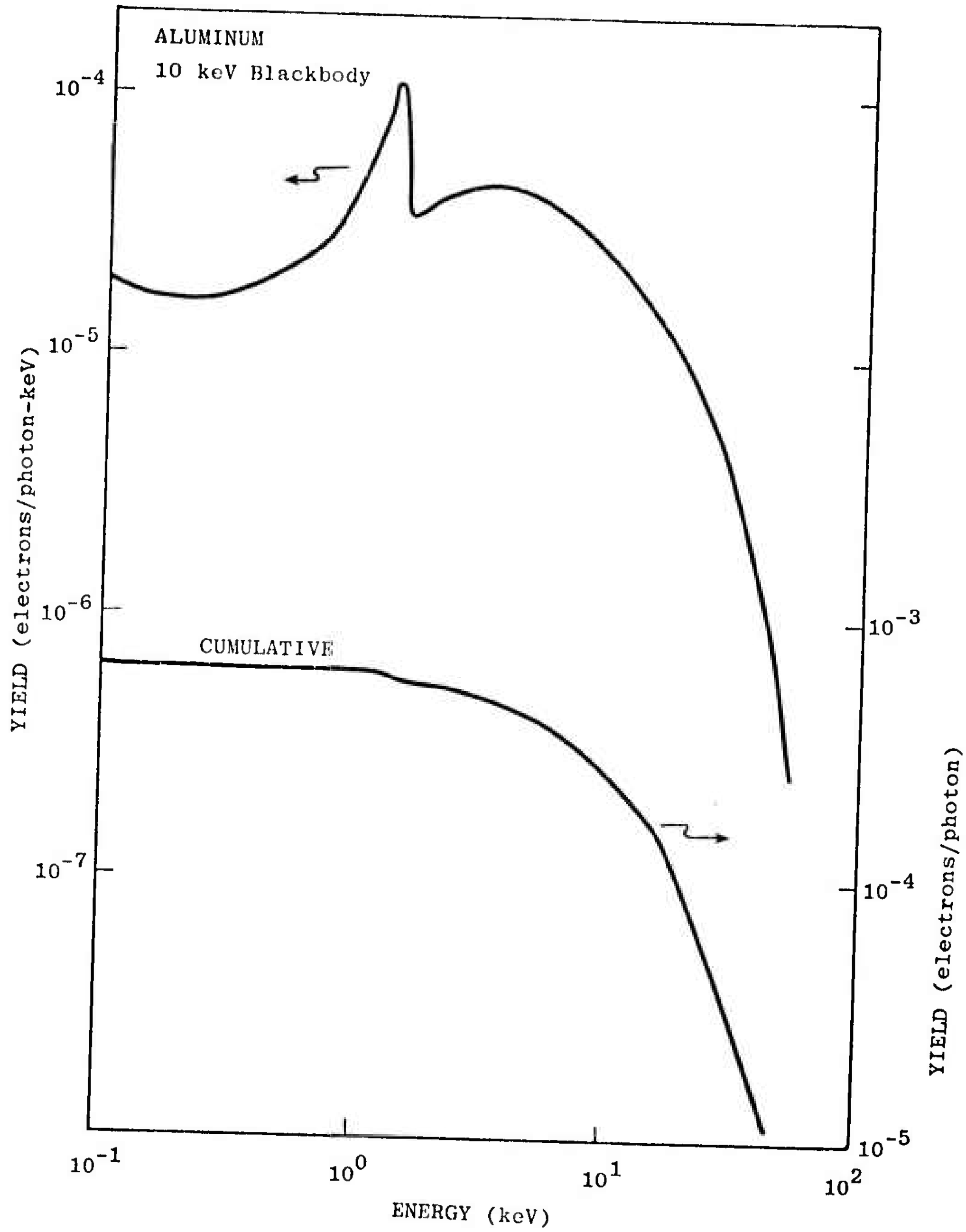

FIGURE 19. Back Yields for a 10 keV Blackbody Spectrum

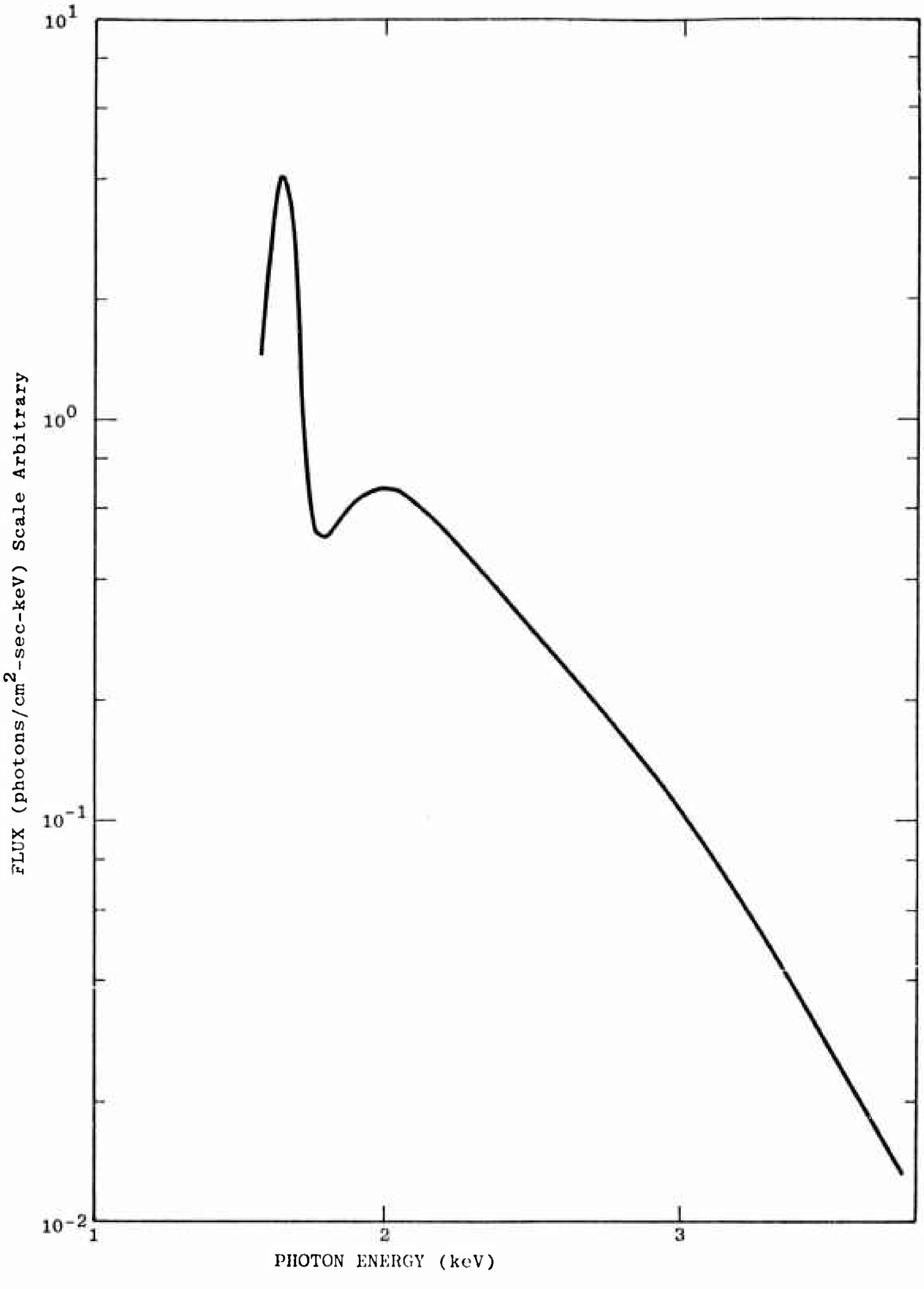

FIGURE 20. Representation of an Exploding Wire Radiation Source

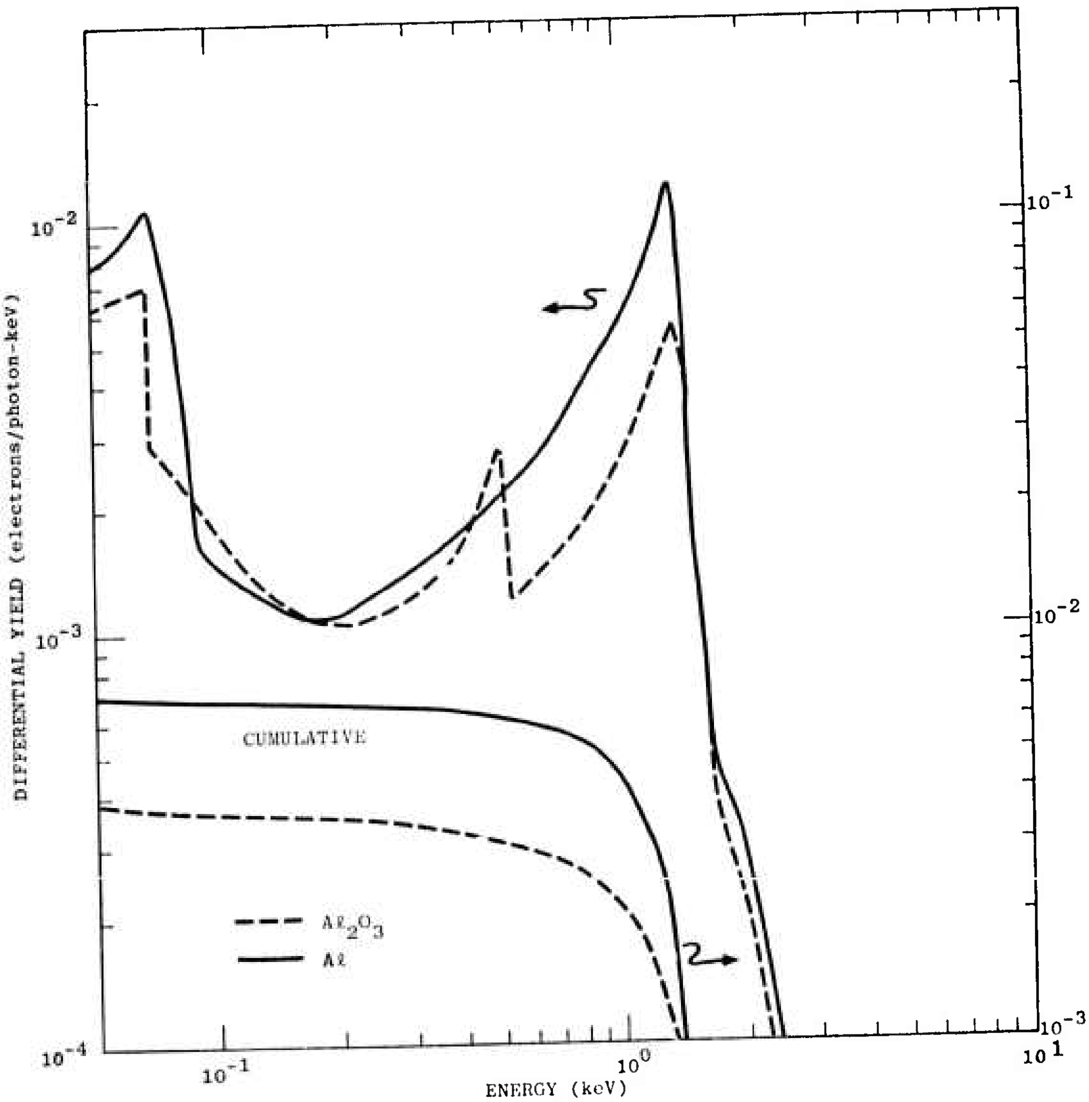

FIGURE 21. Exploding Wire Radiation Back Yields for $A\ell$ and $A\ell_2O_3$

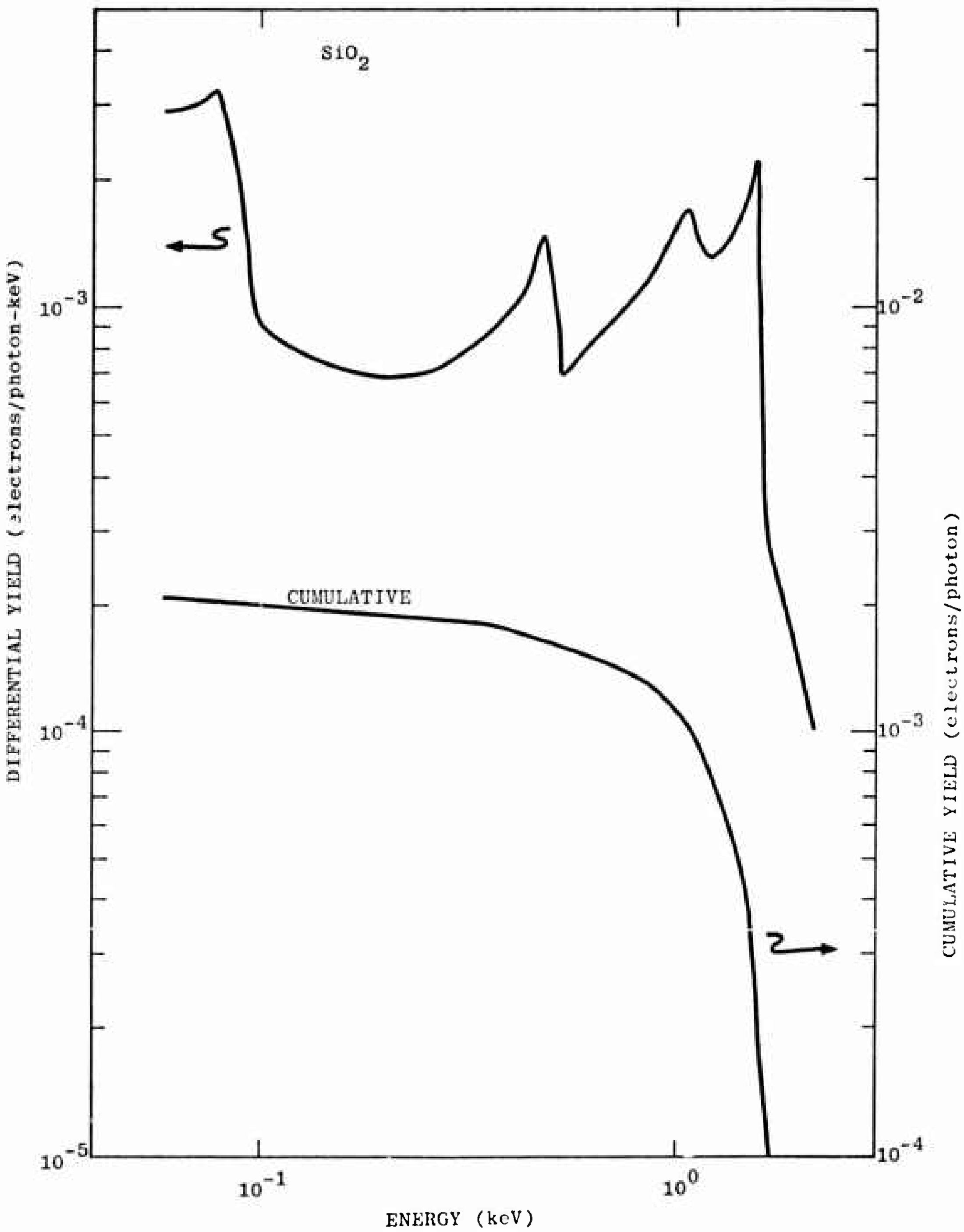

FIGURE 22. Exploding Wire Radiation
Back Yields for SiO_2

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METRIC SYSTEM

BASE UNITS:

Quantity	Unit	SI Symbol	Formula
length	metre	m	...
mass	kilogram	kg	...
time	second	s	...
electric current	ampere	A	...
thermodynamic temperature	kelvin	K	...
amount of substance	mole	mol	...
luminous intensity	candela	cd	...

SUPPLEMENTARY UNITS:

plane angle	radian	rad	...
solid angle	steradian	sr	...

DERIVED UNITS:

Acceleration	metre per second squared	...	m/s
activity (of a radioactive source)	disintegration per second	...	(disintegration)/s
angular acceleration	radian per second squared	...	rad/s
angular velocity	radian per second	...	rad/s
area	square metre	...	m
density	kilogram per cubic metre	...	kg/m
electric capacitance	farad	F	A·s/V
electrical conductance	siemens	S	A/V
electric field strength	volt per metre	...	V/m
electric inductance	henry	H	V·s/A
electric potential difference	volt	V	W/A
electric resistance	ohm		V/A
electromotive force	volt	V	W/A
energy	joule	J	N·m
entropy	joule per kelvin	...	J/K
force	newton	N	kg·m/s
frequency	hertz	Hz	(cycle)/s
illuminance	lux	lx	lm/m
luminance	candele per square metre	...	cd/m
luminous flux	lumen	lm	cd·sr
magnetic field strength	ampere per metre	...	A/m
magnetic flux	weber	Wb	V·s
magnetic flux density	tesla	T	Wb/m
magnetomotive force	ampere	A	...
power	watt	W	J/s
pressure	pascal	Pa	N/m
quantity of electricity	coulomb	C	A·s
quantity of heat	joule	J	N·m
radiant intensity	watt per steradian	...	W/sr
specific heat	joule per kilogram-kelvin	...	J/kg·K
stress	pascal	Pa	N/m
thermal conductivity	watt per metre-kelvin	...	W/m·K
velocity	metre per second	...	m/s
viscosity, dynamic	pascal-second	...	Pa·s
viscosity, kinematic	square metre per second	...	m/s
voltage	volt	V	W/A
volume	cubic metre	...	m
wavenumber	reciprocal metre	...	(wave)/m
work	joule	J	N·m

SI PREFIXES:

Multiplication Factors	Prefix	SI Symbol
1 000 000 000 000 = 10^{12}	tera	T
1 000 000 000 = 10^{9}	giga	G
1 000 000 = 10^{6}	mega	M
1 000 = 10^{3}	kilo	k
100 = 10^{2}	hecto*	h
10 = 10^{1}	deka*	da
0.1 = 10^{-1}	deci*	d
0.01 = 10^{-2}	centi*	c
0.001 = 10^{-3}	milli	m
0.000 001 = 10^{-6}	micro	μ
0.000 000 001 = 10^{-9}	nano	n
0.000 000 000 001 = 10^{-12}	pico	p
0.000 000 000 000 001 = 10^{-15}	femto	f
0.000 000 000 000 000 001 = 10^{-18}	atto	a

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